

NEAR-YRAST SPECTROSCOPY
OF RARE-EARTH NUCLEI.

YRAST ISOMERISM
AND BANDCROSSINGS

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1983



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COSMIC AND SUBATOMIC PHYSICS REPORT
LUIP 8307
LUNFD6/(NFFK-7030)1-24(1983)
ISSN 0348-9329

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NUCLEI YRAST ISOMERISM AND BANDCROSSINGS

BY

STEFÁN G. JÓNSSON
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This thesis contains the following six papers in the field of near-yrast spectroscopy:

- I High-spin states and yrast isomerism in ^{153}Er
Nucl. Phys. A381 (1982) 155
(Lund-Copenhagen collaboration)
- II High-spin band structure in ^{166}Yb
Physica Scripta 24 (1981) 324
(Lund-Copenhagen collaboration)
- III Near-yrast spectroscopy of $^{165-167}\text{Yb}$
Nucl. Phys. A382 (1982) 125
(Lund-Copenhagen collaboration)
- IV High-spin properties of ^{163}Yb ; Band crossings
and signature-splitting in Yb nuclei
Nucl. Phys. A394 (1983) 269
(Copenhagen-Lund collaboration)

V Near-yrast spectroscopy of ^{164}Yb
and neighbouring nuclei
Cosmic and Subatomic Physics Report LUIP 8304
LUNFD6/(NFFK-7027) 1-39 (1983) ISSN-0348-9329
(Lund-Copenhagen collaboration)

VI Experimental results on the study of
high-spin states in ^{165}Lu
Cosmic and Subatomic Physics Report LUIP 8305
LUNFD6/(NFFK-7028) 1-21 (1983) ISSN-0348-9329
(Lund-Copenhagen-Oslo collaboration)



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1. Introduction

The papers presented here deal with high-spin states in rare-earth nuclei. The most efficient way of reaching high-spin states in these nuclei is by heavy-ion (HI) fusion reactions. The nuclei investigated, ^{153}Er , $^{163-167}\text{Yb}$ and ^{165}Lu were produced in (HI,xn) reactions using the ^{12}C and $^{16-18}\text{O}$ beams from the Niels Bohr Institute tandem accelerator in Riso. The beam energies were kept close to the maximum available ones, about 65 MeV for ^{12}C and 85 MeV for $^{16-18}\text{O}$. Isotopically enriched targets of $^{144,149,150,152,154}\text{Sm}$ and ^{153}Eu were used in the different experiments. The spins reached in the rotational nuclei (Yb and Lu) are usually of the order of $15-25\hbar$ for the different cascades depending on their intensity. This is high enough in frequency to make a systematic study of bandcrossings, due to the alignment of $13/2$ neutrons, possible.

During the years in which these studies were being carried out, there have been great improvements in both detector techniques and in heavy-ion accelerators. In our work this is best reflected by the introduction of an array of Ge(Li) detectors surrounded by a NaI(Tl) shield for the suppression of the Compton background¹⁾ for the study of $\gamma\text{-}\gamma$ coincidences. Recent detector set-ups like the crystal-ball, together with heavier ions are moving discrete γ -ray spectroscopy up in the spin region, approaching $40\hbar$ for the yrast sequence in rotational nuclei.

2. Background to the papers

2.1. Theoretical background

Yrast states are the lowest excited states for a given angular momentum. Thus, the yrast line gives the lower limit for excited states, when energy is represented as a function of angular momentum. There is an upper limit of angular momentum that a nucleus can carry before fission takes place (see fig. 1).

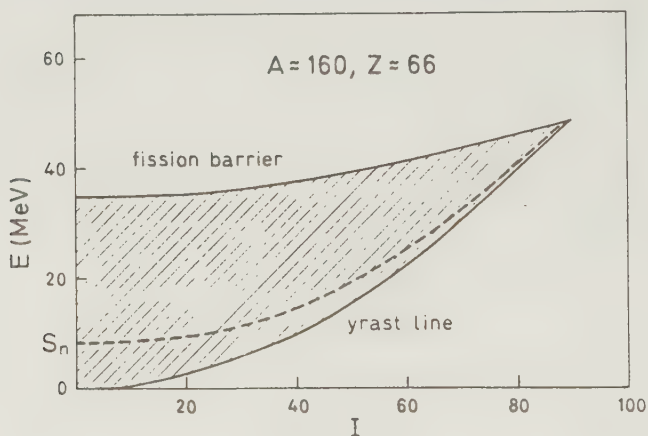


Fig. 1. Excitation energy versus angular momentum diagram based on the liquid-drop model. The dotted curve gives the effective separation energy for removal of a neutron with angular momentum $l=6$, which represents approximately the largest angular momentum for a bound nucleon in this nucleus. The fig. is from ref. ²).

In a compound nucleus reaction, the angular momentum of the compound nucleus depends upon the beam energy and the target-projectile combination. The compound system has a high excitation energy and lies therefore far above the yrast line. The reduction of the excitation energy takes place usually first by evaporation of one or more neutrons, each carrying away about one unit of angular momentum. For lighter or neutron-deficient nuclei emission of charged particles, such as protons and α particles, may compete. When approaching the yrast line, the nucleus still carries large angular momentum. About one neutron separation energy above the yrast line the de-excitation proceeds through a series of γ -rays. Most of the nuclear structure information comes from investigations of the γ -ray spectrum.

Basically, there are two ways of building up angular momentum in nuclei. One way is by the spin-alignment of a few individual nucleons, when the angular momentum is directed along the symmetry-axis. In this case collective rotations do not contribute to the angular momentum. Thus, the total angular momentum is the sum of those of the individual nucleons. Changes in the total angular momentum are obtained by a rearrangement of nucleons in the single-particle orbits. Consequently the spacing of energy levels is rather irregular. The transitions connecting yrast levels are usually of dipole or quadrupole character but sometimes even higher multipole transitions occur. The other way is by a collective rotation in nuclei rotating perpendicular to the symmetry-axis. These nuclei have

prolate shapes and their excited states consist of collective bands obtained by small changes in the motion of a large number of nucleons. The levels within a band are regularly spaced and connected by collective quadrupole transitions.

In a rotating nucleus the Coriolis force counteracts the pairing force. Thus, the pairing correlations are reduced as the rotational frequency is increased. The Coriolis force acts most strongly on particles in high-j orbits. Therefore pairs in a high-j orbit should be the first to be decoupled from the core, with increasing frequency, and their angular momenta aligned along the rotational axis.

Looking at the rare-earth region, $Z=64$ and $N=82$ may be treated as magic numbers. When adding a few particles to this core, $^{146}_{64}\text{Gd}_{82}$, one gets spherical or slightly oblate nuclei, whose excited states can be considered as excited single particle states. The decay pattern of these nuclei is therefore irregular and one can expect isomeric states with half-lives of nanoseconds or more. In a survey experiment ³⁾ this was proven to be the case for several nuclei centered around $N=84$. However, very little information was available on the structure of these isomeric states. This initiated several studies on the structure of these nuclei, among them our study of ^{153}Er .

For heavier nuclei the shape of the nuclear ground state suddenly changes to prolate when going from $N=88$ to $N=90$. The prolate nuclei exhibit a series of rotational

sequences. The level energies can in the first approximation be given by the formula ⁴⁾

$$E_I = \frac{\hbar^2}{2\mathcal{I}} I(I+1)$$

where $\mathcal{I}$ is the moment of inertia of the deformed nucleus and I is the angular momentum of the level. Some years ago an irregularity called backbending was discovered ⁵⁾ in the yrast sequence of levels in even-even nuclei at an angular momentum of about $14\hbar$. This has been interpreted ⁶⁾ as a crossing of two rotational bands, the ground-state band and the Stockholm-band. At the frequency ($\hbar\omega$) corresponding to this crossing, a pair of $i_{13/2}$ neutrons is breaking up, thereby causing a sudden increase of the moment of inertia. Similar crossings can be expected for other rotational bands. A number of well-deformed even- Z nuclei have been investigated recently, among them $^{163-167}\text{Yb}$. Weakly populated side-bands have been observed to high-spin states giving information about higher frequency bandcrossings. Systematics of quasineutron configurations is thus beginning to emerge. In order to establish similar systematics for quasiproton states, studies of odd- Z nuclei have been initiated, one of them being ^{165}Lu presented here.

The theoretical models describing rotational nuclei are the particle-rotor model and the cranked shell model (CSM). In the particle-rotor model the majority of the nucleons are represented by a rotor having only rotational degrees of freedom. The degrees of freedom of the remaining nucleons are treated explicitly. The calculations are performed in the laboratory system and

properties of the different states are represented as functions of angular momentum. In the case of both the odd-N Yb nuclei and in the case of ^{166}Yb , some particle-rotor calculations were made. Within the cranked shell model the rotational bands are interpreted as quasiparticle configurations moving in a rotational potential. Therefore, the rotational frequency, $\hbar\omega$, is a fundamental property in these studies. The theoretical description of the cranked shell model is based on the single particle routhian

$$h'_{sp} = h - \omega j_x$$

which is the Hamiltonian in a reference frame rotating with an angular frequency ω around the x-axis. j_x is the projection of the spin on the x-axis. One of the symmetric properties of the single particle routhian is its invariance with respect to a rotation R_x around the x-axis by an angle π

$$R_x h'_{sp} R_x^{-1} = h'_{sp} \quad \text{where} \quad R_x = e^{-i\pi j_x}$$

The single particle states $|\alpha i\rangle$ can be classified according to their symmetry with respect to R_x

$$R_x |\alpha i\rangle = e^{-i\pi\alpha} |\alpha i\rangle$$

In this way α , the signature of the state, is defined. It is an additive quantity and takes the values $\alpha = \pm 1/2$ for single particle states. The total angular momentum of a configuration is restricted by the total signature according to the relation

$$I = \alpha_t \pmod{2}$$

In order to compare CSM calculations and experimental results they have to be presented in the same reference frame. Transformations of the experimental information

into a rotating frame is described in ref. ⁷). The excitation energies in the rotating frame (the routhians, ϵ') and the projection of the angular momentum of the quasiparticles on the rotational-axis (the alignment, i_x) can be extracted. Detailed comparison between CSM calculations and experimental results were made for the Yb nuclei.

2.2. Experimental background

Gamma-gamma coincidence studies and γ -ray angular distribution measurements are a common feature for all the studies reported here. They are also the most important ones, when constructing the level schemes.

The simplest way to measure γ - γ coincidences is to use two Ge(Li) detectors and to accept signals when two γ -rays, one in each detector, are detected within a certain time interval. In order to increase the counting rate, more than two detectors can be used. Four Ge(Li) detectors were used in the first measurement of ¹⁵³Er. Coincidences between one of them and any one of the other three were recorded. In the case of ^{166,167}Yb four Ge(Li) detectors, together with a multiplicity filter of four NaI(Tl) crystals were used. An event is accepted if a coincidence between at least three counters is recorded, of which at least two must be Ge(Li) detectors. The purpose of the multiplicity filter is to remove low multiplicity γ -rays, e. g. the ones due to the radioactive background. A further improvement in the study of γ - γ coincidences is an

array consisting of five Compton suppressed Ge(Li) detectors. An event is accepted if there is a coincidence between at least two detectors. The Compton suppression reduces the background considerably and makes it possible both to identify weak transitions in the gated spectra and to gate on weak transitions. This array was used in the studies of ^{153}Er and $^{163,164,165}\text{Yb}$ and together with one NaI(Tl) crystal as a multiplicity filter in the study of ^{165}Lu .

Different detector arrangements were used in the angular distribution measurements, like a single Ge(Li) detector, a low energy photon detector (LEP) and a Ge(Li) detector Compton suppressed by a NaI(Tl) or a BGO (bismuth germanate) shield. A singles γ -ray spectrum is recorded at different angles when moving the detector set-up around the target. A Ge(Li) detector is used as a monitor. The Compton suppressed set-ups have again been shown to be very valuable in reducing of the background. The LEP detector has a very good resolution and can therefore be used to obtain angular distribution coefficients and relative intensities for low energy γ -rays up to roughly 300 keV, even when the spectra are very complex.

Many other experiments were done for one or more of the nuclei, depending on their properties and the questions arising on each occasion. These experiments will be mentioned in the presentation of the papers.

3. Presentation of the papers

3.1. Paper I

The existence of isomeric states had been predicted in the region $Z \geq 64$ and $N \geq 82$ and experimentally confirmed in a survey work. In the nucleus $^{153}_{68}\text{Er}_{85}$ several isomeric states could thus be expected.

The level structure of ^{153}Er was unknown prior to this study. The reaction $^{144}\text{Sm}(^{12}\text{C}, 3n)$ was used for populating high-spin states in ^{153}Er . The $2n$ and $3n$ reaction channels, were for the bombarding energies used, the most favourable ones, giving ^{154}Er and ^{153}Er , respectively. Due to the neutron deficiency of the compound nucleus the emission of charged particles can compete, resulting in a cross section of a few percent for the $\alpha 2n$ channel, giving ^{150}Dy , and for the $p 2n$ channel, giving ^{153}Ho .

Several investigations were made in addition to the γ - γ coincidence and γ -ray angular distribution measurements. The transitions belonging to ^{154}Er and ^{153}Er were separated by sum spectrometer and excitation function measurements. The study of the average multiplicities of the γ -rays, as a function of the bombarding energy was made. A search for delayed γ -rays and transitions feeding isomeric levels was performed in a delayed coincidence experiment using a pulsed beam. A conversion electron measurement was done in the energy range around 700 keV. From the other experiments 712.0 keV was presumed to be an

isomeric transition and its properties are crucial in explaining the configuration of the isomer.

In the delayed coincidence experiment, five γ -rays, being previously assigned to ^{153}Er , showed a common half-life of 373 ± 9 ns. The time distribution for one of them, the 712.0 keV transition, showed no prompt component, indicating that it might depopulate the isomeric state. The multiplicity of this γ -ray is around 5-6, independent of the bombarding energy E , and the multiplicities of the other four are about two units higher and increase with increasing E . This constant multiplicity is a further indication that the 712.0 keV γ -ray is an isomeric transition. The higher multiplicities for the other transitions mentioned are due to side-feeding. The angular distribution for the 712.0 keV is isotropic, as expected for an isomeric transition. The conversion coefficient measurement gave an E3 or M1 character for this transition, the former being in agreement with it depopulating the isomeric state. The spin and parity for this state would then be $27/2^+$, which could be explained to be due to a $h_{9/2}((f_{7/2})^2 \times 3^-)$ coupling.

The level scheme of ^{153}Er was constructed using the results of the experiments mentioned before. The $11/2^-$ and $15/2^-$ members of the $vf_{7/2}^3$ multiplet were observed. So were also the $13/2^+$, $17/2^+$, $21/2^+$ and $25/2^+$ states explained as $vf_{7/2}^3 \times 3^- + vi_{13/2} f_{7/2}^2$ and the $9/2^-$, $13/2^-$, $17/2^-$ and $21/2^-$ states belonging to the $vh_{9/2} f_{7/2}^2$ multiplet. This is in good agreement with observations in other $N=85$ nuclei.

A cascade by-passing the isomer was also seen and a few transitions were placed above the isomer.

3.2. Paper II

High-spin states in ^{166}Yb were populated in the $^{154}\text{Sm}(^{16}\text{O}, 4n)$ reaction at 80 MeV. Gamma-gamma coincidence and γ -ray angular distribution measurements were made. A conversion electron measurement was made in the energy range 600-1200 keV, this region containing most of the interband transitions.

On the basis of these experiments a level scheme was constructed. The ground-state band was established to its 18^+ state, and the S-band from the 12^{+} state to the 24^{+} state. Two negative parity bands, one with odd spin and the other with even spin, were constructed to 23^- and 22^- , respectively. A cascade with unknown spins and parities was observed, as well as a few transitions belonging to the γ -band.

Calculations according to the particle-rotor model were done and they reproduce fairly accurately the energies in the ground-state band and the S-band, as well as the observed branchings from levels in these bands. Experimental routhians and alignments were plotted. The ground-state band S-band crossing takes place at $\hbar\omega \approx 0.28$ MeV, and the gain in alignment at this frequency is about $8\hbar$.

3.3. Paper III

This paper deals with experimental studies on $^{165,167}\text{Yb}$ and discusses these results together with those of the previously investigated ^{166}Yb .

The reaction $^{152}\text{Sm}(^{17}\text{O},4\text{n})$ at 80 MeV was used in the study of ^{165}Yb . Gamma-gamma coincidence, γ -ray angular distribution and conversion electron measurements were made.

The γ - γ coincidence study of ^{167}Yb was made using the $^{154}\text{Sm}(^{17}\text{O},4\text{n})$ reaction at 80 MeV. In the angular distribution experiment the reaction $^{154}\text{Sm}(^{18}\text{O},5\text{n})$ at 84 MeV was used.

The favoured and unfavoured members of the band based on the $5/2^+(642)$ Nilsson orbital were observed up to $49/2^+$ and $39/2^+$ for ^{165}Yb and $53/2^+$ and $43/2^+$ for ^{167}Yb . The ground state band $5/2^-(523)$ was established up to $53/2^-$ for ^{165}Yb and $49/2^-$ for ^{167}Yb . The other signature of this band was seen only in ^{165}Yb from $27/2^-$ to $51/2^-$.

Experimental routhians and alignments were constructed in order to compare the different results and to make comparisons with CSM calculations. In both $^{165,167}\text{Yb}$ three bands, based on single-quasineutron configurations, are seen and labelled as $(-,+)_1$, $(+,+)_1$ and $(+,-)_1$. Multiple-quasineutron states can be constructed from these single-quasineutron states and compared to the experimental ones.

The agreement between the constructed and the experimental two-quasineutron configurations in ^{166}Yb is good. This indicates that a residual interaction between the two unpaired quasineutrons is not strongly dependent on frequency or configuration. The constructed three-quasineutron configurations give larger alignment than the ones experimentally observed in $^{165,167}\text{Yb}$. This might be due to a reduction in pairing.

The results of the CSM calculations reproduce well the experimental results for two-quasineutron configurations. For three-quasineutron configurations a larger alignment is predicted than is observed. By reducing Δ in the CSM calculations, the experimental values can be reproduced. Problems associated with the predicted crossing in the $(+,+)_1$ band are discussed. This bandcrossing is due to the alignment of a different pair of $i_{13/2}$ quasineutrons than those causing the lower frequency bandcrossing in the negative parity band and in the yrast band of the neighbouring even-N isotopes. This bandcrossing is observed about 50 keV higher in ^{165}Yb than predicted. The crossing frequency can be increased in the calculations by increasing the pairing-correlation parameter. However, this is not very likely and the discrepancy in the case of ^{165}Yb is not well understood.

Signature dependence is expected for M1-transition matrix elements connecting the different signatures in rotational bands based on high-j, low-Q quasiparticle orbits. The B(M1) values for the transitions between the $(+,+)_1$ and

$(+, -)_1$ bands in $^{165, 167}\text{Yb}$ were calculated and compared with particle-rotor model calculations. The results are in good agreement with what is expected.

3.4. Paper IV

High-spin states of ^{163}Yb were studied in the $^{149}\text{Sm}(^{18}\text{O}, 4n)$ reaction at 84 MeV. Gamma-gamma coincidence, γ -ray angular distribution and conversion electron measurements were made. In order to study low energy delayed transitions, a γ - γ -time experiment was done.

The yrast cascade was extended up to the $49/2^+$ level. The unfavoured portion of the $i_{13/2}$ band was constructed up to the $39/2^+$ level. The bands labelled $(-, +)_1$ and $(-, +)_2$ were established up to the $45/2^-$ and $37/2^-$ levels, respectively. Band $(-, -)_1$ was seen up to $47/2^-$. Half-lives of two low-lying levels were determined. A cascade previously placed in ^{163}Yb is not assigned to this nucleus in our study.

Systematics of bandcrossing frequencies and signature splitting were summarized for odd-N Yb isotopes. The bandcrossing in the yrast sequences of the odd-N isotopes is about 0.08 MeV higher than the crossing in the yrast sequences of the even-N isotopes. This is because one of the $i_{13/2}$ quasineutrons, aligning at around 0.27 MeV in the even-N isotopes, is occupied in the odd-N isotopes. On the other hand the, bandcrossing in the negative parity bands should correspond to the bandcrossing in the yrast

band in the even- N nuclei, because both the $i_{13/2}$ quasineutrons causing this crossing are free. However, this bandcrossing is observed at about 0.04 MeV lower than expected. This has been explained as a reduction in pairing due to the negative parity quasineutron.

Signature splitting is a measure of the $\Omega=1/2$ component in the wave function. The signature splitting decreases for the lowest positive parity configurations when going from ^{161}Yb to ^{165}Yb . This is due to the shift of the Fermi surface, with increasing N , away from the $1/2^+(660)$ Nilsson state.

CSM calculations were done and comparison with experimental results was made. The observed bandcrossing in the yrast band is about 20 keV higher than predicted, compared with 50 keV in ^{165}Yb . As in the other odd- N isotopes at higher frequencies, a larger alignment is predicted than is observed. For the positive parity bands a positive signature splitting is observed as well as predicted. However, it is predicted to be smaller in the odd- N isotopes than what is observed. The $(-, -)_1$ band is observed lower in energy than the $(-, +)_1$ band at higher frequencies. This is surprising since this negative decoupling in energy in the negative parity band is neither in agreement with CSM calculations nor found in any nucleus in the $N=90-102$ mass region.

The $B(M1)$ values for the transitions between the $(+, +)_1$ and $(+, -)_1$ bands were calculated from the transition

intensities and the results are in good agreement with what is expected.

3.5. Paper V

In the study of γ - γ coincidences and γ -ray angular distributions in ^{164}Yb , the reaction $^{152}\text{Sm}(^{16}\text{O},4n)$ was used. Gamma-gamma coincidences were measured at 84 MeV and the angular distribution measurement was made at 81 MeV. Conversion electron measurements were made in the energy range 300-1200 keV, using the $^{150}\text{Sm}(^{18}\text{O},4n)$ reaction at 83 MeV.

The level scheme of ^{164}Yb was constructed. The ground-state band was extended up to 22^+ and the S-band to 26^+ . Three negative parity bands were constructed up to 23^- , 24^- and 18^- for the bands labelled $(-,1)_1$, $(-,0)_1$ and $(-,0)_2$, respectively. Some low lying levels were seen.

Experimentally observed two-quasineutron configurations in ^{164}Yb are compared with the ones constructed from single-quasineutron configurations in the neighbouring odd-N Yb isotopes. The observed energy splitting between the configurations $(-,1)_1$ and $(-,0)_1$ is larger than the constructed one and the alignment of the $(-,0)_2$ configuration is much smaller.

The one- and three-quasiparticle configurations in $^{163,165}\text{Yb}$, together with the constructed two-quasiparticle configurations can be used to get information on the

residual interaction between quasiparticles. The values obtained in this way for V_{AB} , V_{AE} , V_{BE} and V_{BF} are all negative and of the order of 0.1-0.2 MeV, except the ones for V_{BF} , which are considerably larger.

The g-band S-band crossing takes place at $\hbar\omega \approx 0.28$ MeV. The ground-state band experiences another bandcrossing soon after the crossing with the S-band. The cranked shell model predicts that this crossing corresponds to the alignment of a second pair of $i_{13/2}$ quasineutrons. The gain in alignment at this crossing, however, implies that this is a crossing between bands based on zero and four quasiparticles.

The discrepancies between constructed and experimental two-quasineutron side-bands are hardly consistent with the CSM interpretation of the three negative parity bands as AE, AF and BE. In order to explain the structure of the negative parity bands in ^{164}Yb a detailed comparison with the corresponding bands in ^{166}Yb and $^{162,164}\text{Er}$ is made. The $(-,1)_1$ band in ^{164}Yb probably begins as an octupole-band at low frequencies. At higher frequencies it interacts strongly with an unobserved AE band but never reaches the pure AE structure. The $(-,0)_1$ band has most likely an almost pure two-quasineutron structure, AF, above the band interaction at $\hbar\omega \approx 0.20$ MeV. At lower frequencies the structure is probably more complex, involving components of the $3/2^-(521)$ level. It is difficult to explain the structure of the $(-,0)_2$ band. Some suggestions can be made from the observations such as

it being a proton band or that the B level is occupied.

Bandcrossing frequencies and the gain in alignment are summarized for the Yb nuclei and some of the most important features discussed. The AB crossing frequency is lower in the odd-N isotopes than in the even ones. The pairing contribution is blocked from a quasineutron orbit near the Fermi surface, causing a reduction in the pairing correlation parameter and thus reducing the crossing frequency. This reduction is almost the same in all the odd-N Yb isotopes. Another systematical behaviour is the reduction in Δi in the odd-N isotopes compared with the even ones. For the N=90,92,94,96 Yb isotopes the gain in alignment decreases with increasing neutron number.

The data are not as complete for the BC crossings as for the AB crossing. When comparing the crossing frequencies for crossings between different quasineutron configurations, the blocking argument seems to work, except near N=90. The crossing frequencies in the side-bands are considerably higher than the AB crossing frequency. Thus, these bandcrossings are due to the alignment of a pair of $i_{13/2}$ neutrons other than those responsible for the AB crossing.

CSM calculations were made and compared with the experimental results. The alignment of the S-band is reproduced fairly well. The observed signature splitting between the $(-,0)_1$ and $(-,1)_1$ bands is larger than predicted for the AE and AF configurations and the

alignment of the $(-,0)_2$ band is smaller than the alignment of the BC configuration.

3.6. Paper VI

No level scheme information existed for the odd-Z nucleus ^{165}Lu prior to this study. However, the ground-state of the nucleus had been measured to be $1/2$. The reaction $^{153}\text{Eu}(^{16}\text{O},4n)$ was used to populate high-spin states in this nucleus. Gamma-gamma coincidences were measured at 84 MeV and the angular distribution of the γ -rays at 84.5 MeV.

This reaction resulted in many coincident cascades. To make a correct assignment to ^{165}Lu , an excitation function measurement was made. An attempt to find low energy delayed transitions connecting different bands was made in a γ -time experiment.

Five rotational bands were assigned to ^{165}Lu . In four of these bands, both signatures were seen. These bands were assigned to be built on the Nilsson configurations $5/2^+(402)$, $1/2^+(411)$, $1/2^-(541)$, $7/2^+(404)$ and $9/2^-(514)$ from the systematics of heavier odd-N Lu nuclei. The first three bands mentioned are connected and so are the last two but no transitions between these two groups have been found.

The routhians and alignments were calculated. The crossing frequency due to the first pair of $i_{13/2}$ neutrons should

be expected at about the same frequency as in even-even nuclei, because the odd proton should not influence the pairing. The crossing frequency in the sequences built on the $7/2^+(404)$ configuration turns out to be 0.275 MeV, as expected. In the negative parity bands built on the $9/2^-(514)$ configuration the crossing frequency is reduced by about 20 keV and the interaction is much weaker. The $\alpha=1/2$ band built on the $1/2^-(541)$ Nilsson state is only observed up to the backbending region, but the crossing frequency can be estimated to be at least 0.32 MeV. The increased crossing frequency in this band has been observed earlier in other nuclei and can be explained partially by increased deformation. At this moment there is no satisfactory explanation to the variation in crossing frequency depending on which proton configuration is involved.

Acknowledgements

I want to express my sincere gratitude to my supervisor, Professor Hans Ryde, who has introduced me to this interesting field of nuclear physics. Our many discussions during the analysis were very valuable and a great support in continuing the work.

I also want to thank all my coworkers, from different parts of the world, for their excellent collaboration.

I am grateful to the technical staff at the tandem accelerator laboratory in Risø for their support, and to the people who made the drawings and assisted in other ways to get this work ready.

I want to thank all my colleagues at the Department of Physics for these years.

I would like to thank my parents very much for their support and encouragement over the years.

Finally, I want to thank specially my wife and our children for their great help during these years. Without their support and tolerance this work could not have been done. Thank you once more.

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HIGH-SPIN STATES AND YRAST ISOMERISM IN ^{153}Er

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Received 10 December 1981

Abstract: Energy levels in ^{153}Er have been populated in the reaction $^{144}\text{Sm}(^{12}\text{C}, 3n)^{153}\text{Er}$. Isotopically enriched targets were bombarded with 53–65 MeV ^{12}C ions and the emitted γ -ray and conversion electron spectra were investigated. From studies of excitation functions, γ - γ coincidences, γ -ray multiplicities, delayed γ -radiation and angular distributions, the level scheme of ^{153}Er has been constructed. The properties of the energy levels are discussed and compared with the results of calculations with a deformed shell model. The remarkable similarities and some important discrepancies of the level structure, when compared with adjacent $N = 85$ nuclides, are emphasized.

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NUCLEAR REACTION $^{144}\text{Sm}(^{12}\text{C}, 3n)$, $E = 53\text{--}65$ MeV; measured E'_γ , $I_\gamma(E)$, $I_\gamma(t)$, $I_\gamma(\theta)$, mean values and standard deviations of γ -ray multiplicities, $I(\text{ce})$. ^{153}Er deduced levels, J , π , $T_{1/2}$. Enriched targets, Ge(Li), Ge, NaI(Tl) detectors, Compton suppression, mini-orange electron spectrometer with Si(Li) detector.

1. Introduction

The level structure of light rare-earth nuclei with $Z \geq 64$ and $N \geq 82$ has recently been discussed ¹⁾ in terms of the independent-particle model with the semi-closed shell nucleus ^{146}Gd acting as a core. The properties of high-spin states along the yrast line were early discussed ^{2–4)} and the predicted existence of isomeric states in this region was experimentally confirmed in a survey work ⁵⁾. The response of the core to the polarizing effect of a successively increasing number of valence nucleons is an intriguing question. It has thus been pointed out ⁶⁾ that high spin isomers seem suddenly to disappear for $N > 87$. The abrupt transition to prolate shapes of the nuclear ground states when going from $N = 88$ to $N = 90$ has been well known for a long time.

A series of even- Z isotones having $N = 85$ has been studied by many groups. The

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nuclide ^{145}Nd with $Z = 60$ has been investigated by Hammarén *et al.* ⁷⁾, ^{147}Sm by Kownacki *et al.* ⁸⁾ and by Piiparinen *et al.* ⁹⁾, ^{149}Gd and ^{151}Dy by Piiparinen *et al.* ^{10, 11)}. In the present paper the properties of the nucleus ^{153}Er with $Z = 68$ are discussed. When this investigation started the level structure of this nuclide was completely unknown. The first results establishing the decay of a 373 ns isomer at 2751 keV in ^{153}Er are reported elsewhere ¹²⁾. Several groups ^{13–16)} have registered the existence of an additional isomeric state at around 5 MeV. Recently a detailed spectroscopic study of high-spin single-particle states in ^{153}Er has been performed by Horn *et al.* ¹⁶⁾ using various nuclear reactions. Their results are partly complementary to the present ones as higher projectile energies were used.

2. Experiments and results

Energy levels in ^{153}Er were populated in the $^{144}\text{Sm}(^{12}\text{C}, 3n)^{153}\text{Er}$ reaction. Isotopically enriched ($> 95\%$), 1–4 mg cm² thick ^{144}Sm targets mounted onto lead backings were bombarded with 53–65 MeV ^{12}C ions from the NBI Tandem Accelerator. Gamma-ray spectra were analysed using the computer code CARATE ¹⁷⁾.

When the present investigations were started, no transitions in ^{153}Er were known. Gamma-rays due to transitions in this nucleus were distinguished from those in ^{154}Er , the other dominating product nucleus, with a sum-spectrometer ¹⁸⁾ set-up. This consisted of a large cylindrical NaI(Tl) crystal supplemented by two Ge(Li) counters placed at 90° to each other. The solid angle subtended by the NaI(Tl) detector was 70% of 4 π , giving a high efficiency for the total γ -radiation to be detected.

In the $^{144}\text{Sm}(^{12}\text{C}, 3n)^{153}\text{Er}$ reaction, there is less energy available for γ -radiation after the evaporation of three neutrons than is the case for the 2n channel. Consequently in the low-energy part of the spectrum recorded by the NaI(Tl) detector transitions in ^{153}Er are much stronger than in the high energy part, which is dominated by transitions in ^{154}Er . The γ -ray spectra obtained with one of the Ge(Li) detectors in coincidence with the low-energy and high-energy parts of the sum spectrum, respectively, are compared in fig. 1. The ratio of the γ -ray intensities in the two spectra is an order of magnitude larger for transitions in ^{153}Er than for transitions in ^{154}Er . The large peaks not belonging to ^{153}Er , that are visible only in the upper spectrum, are due to radioactive background.

A further support for the isotopic assignment of the γ -rays comes from the study of their excitation functions using ^{12}C beams of $E = 53.0$ –64.5 MeV. Two classes of strong transitions were easily identified, one with a yield maximum at around $E = 60$ MeV, the other with monotonically increasing yield, assigned to ^{154}Er and ^{153}Er , respectively. Furthermore, these excitation functions were used for obtaining information about the γ -ray cascades in ^{153}Er nuclei as is demonstrated in fig. 2, where the γ -ray intensities are normalized to that of the 299.4 keV transition to the

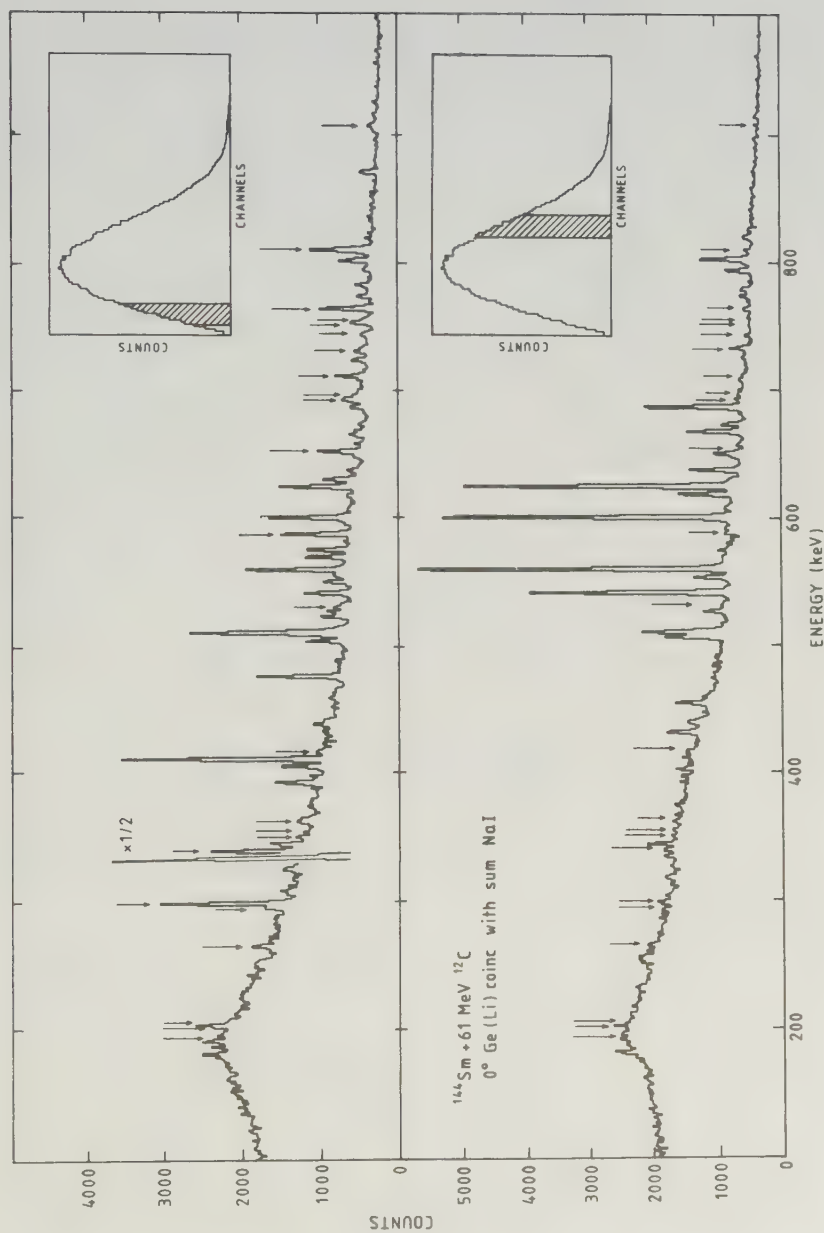


Fig. 1. The Ge(Li) γ -ray spectra obtained with a gate placed on the low-energy part (upper spectrum) and on the high-energy part (lower spectrum) of the sum-spectrum recorded in a NaI(Tl) detector subtending a solid angle of 70° of 4π . The γ -ray energies given in table 1 are marked with arrows.

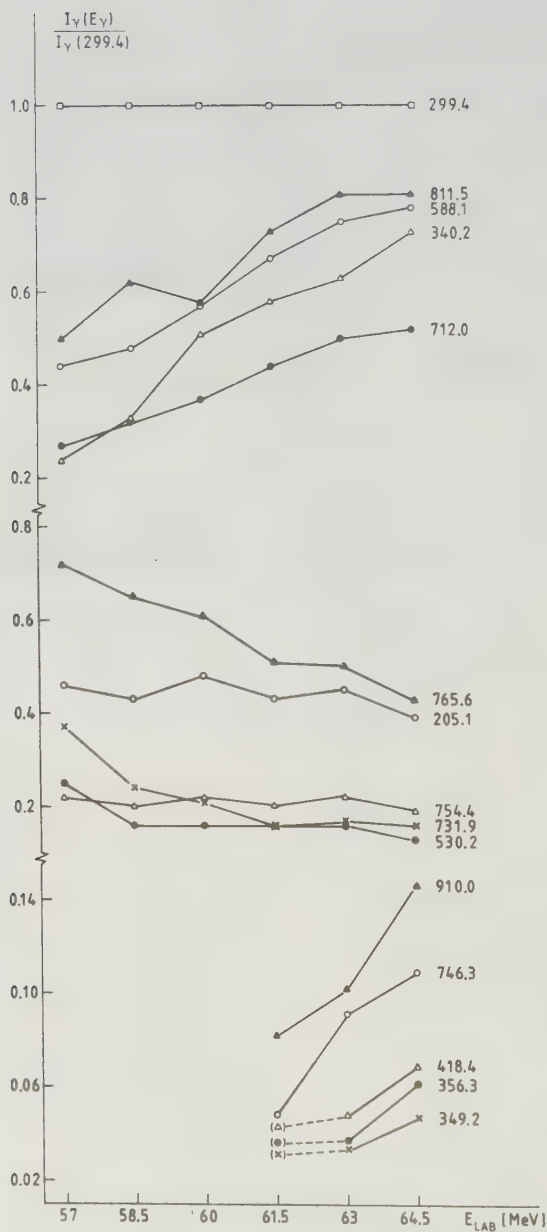


Fig. 2. Excitation functions for some γ -rays assigned to transitions in ^{153}Er and normalized to the intensity of the 299.4 keV γ -line.

ground state. If compared to the level scheme for ^{153}Er , as presented in sect. 3, it is clear that the five transitions associated with the decay of the isomer at 2751 keV get more intensity as the bombarding energy increases. On the other hand the transitions associated with the ground-state band and the positive-parity band decrease in relative intensity for higher beam energies. Finally, the intensities of the transitions associated with the cascade by-passing the 2751 keV isomer show a very steep increasing tendency. These observations are in agreement with the findings of Horn *et al.* ¹⁶⁾, who used a higher bombarding energy and therefore observed hardly any population of the ground-state band or of the positive-parity band.

Integrated relative intensities were obtained from an angular distribution measurement at a bombarding energy of 62.3 MeV, described later in this section. The relative cross sections for the strongest reaction channels observed are about 46 % for ^{153}Er , about 37 % for ^{154}Er , about 8 % for ^{150}Dy and less than 9 % for ^{153}Ho , as measured from the transitions to the ground states.

The average multiplicities $\langle M \rangle$ of the γ -rays were studied as a function of the bombarding energy. One Ge(Li) detector and nine NaI(Tl) counters, compactly mounted [as described in ref. ¹⁹⁾] in the upper hemisphere around the target, were used for the detection of the γ -radiation. Singles γ -ray spectra from the Ge(Li) counter as well as coincidence events between the Ge(Li) detector and one or more of the NaI(Tl) detectors were recorded. The average multiplicity $\langle M \rangle$ and the standard deviation σ of the multiplicity distribution were then deduced for the γ -rays from these data according to the procedure described by Andersen *et al.* ¹⁹⁾. In fig. 3 the average multiplicities are shown for members of the isomeric cascade and a few other transitions in ^{153}Er , at various bombarding energies, together with the standard deviations for the isomeric transitions at 64.5 MeV.

It may be concluded from these results that the members of the cascade deexciting the isomer all show a weakly increasing multiplicity around 7, except for the 712.0 keV γ -ray, which shows a lower multiplicity of between 5 and 6, independent of the bombarding energy. Also the standard deviation of the multiplicity distribution is much smaller ($\sigma = 1.5$) for the 712.0 keV γ -ray than for the other members of the cascade ($\sigma = 3\text{--}4$). These results are consistent with the interpretation of the 712.0 keV γ -ray as being due to an isomeric transition on top of a cascade of altogether five members. The larger values for these other members of the cascade of both the multiplicity and the standard deviation are then due to the side feeding, mainly through the 910.0 keV transition, which by itself – quite naturally – shows even larger values for the multiplicity. These conclusions are also in agreement with the results reported in refs. ¹⁵⁾. They found an average multiplicity of 5.6 ± 1.0 for the delayed cascade and of 8.6 ± 1.0 for the by-passing cascade.

A search for delayed γ -rays and precursors was made by chopping the ^{12}C beam into 600 ns long pulses with a frequency of 1 MHz. Conventional delayed coincidence techniques were applied, using one intrinsic Ge and one Ge(Li) detector for energy measurements together with two NaI(Tl) crystals for timing requirement. In addition

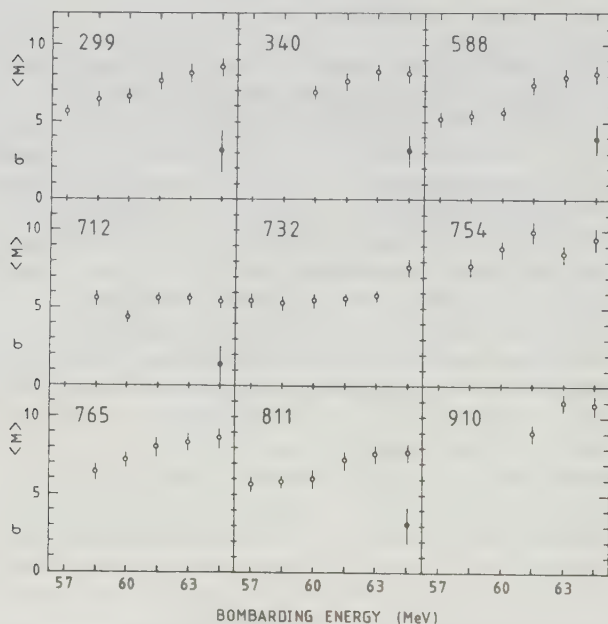


Fig. 3. The average multiplicities (open circles) and standard deviations (filled circles) for some transitions in ^{153}Er as a function of the bombarding energy.

to the γ -rays from the known isomeric state in ^{154}Er with a half-life of 40 ns [ref. ²⁰], five delayed γ -rays with a common half-life of 373 ± 9 ns were recorded. Cf. fig. 4. It should be noted here that the ratios between the prompt and delayed component for these various time distributions also indicate the ordering of the transitions within the cascade. Particularly the absence of a prompt component for the 712.0 keV γ -ray suggests that the corresponding transition de-excites the isomeric state itself*. No delayed γ -rays coming from the isomer reported at around 5 MeV [refs. ¹³⁻¹⁶] were observed. The intensity of the γ -rays connecting levels above 4.5 MeV is, however, too small for them to be detected in our pulsed beam experiment. In the spectra showing transitions feeding the populated isomer, three γ -rays were assigned to ^{153}Er , as will be discussed in sect. 3.

In order to establish the multipolarity of the transitions, the angular distribution of the singles γ -ray spectrum was measured with a Ge(Li) detector at five different angles between $+58^\circ$ and $+148^\circ$ relative to the beam and at the same time with a

* It should be noted that Horn *et al.* ¹⁶) suggest an isomeric transition of 7.5 keV above the 2751 keV level, based on their observation of a prompt component in the 712.0 keV transition together with energy balance calculations.

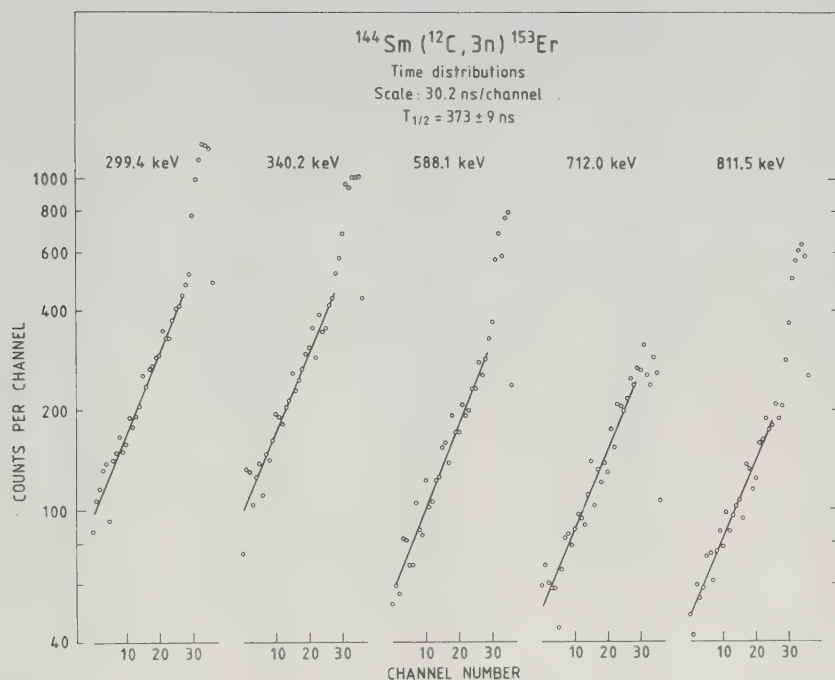


Fig. 4. Time distribution of the intensities of the γ -rays deexciting the 2751.2 keV isomeric state.

second Ge(Li) detector in a Compton suppression set-up at angles between 0° and -90° . A third stationary Ge(Li) detector placed underneath the target served as a monitor. A radioactive source, ^{152}Eu , placed in the target position was used for efficiency calibration of the detectors at the various angles. The measurement was made at a bombarding energy of 62.3 MeV. The peak intensities, normalized to the monitor yields and corrected for the variation of the detection efficiency, were then fitted to the expression $W(\theta) = A_0 + A_2P_2(\cos \theta) + A_4P_4(\cos \theta)$. The two sets of data were in excellent agreement and the values of A_2/A_0 and A_4/A_0 measured with the single Ge(Li) detector are given in table 1 together with the integrated relative intensities.

It is interesting to note here that the 712.0 keV γ -radiation comes out isotropic, which would be expected for an isomeric transition. The other members of the delayed cascade show angular distributions characteristic of attenuated quadrupole radiation, with the exception of the 299.4 keV transition, which is of dipole character.

As the properties of the 712.0 keV transition are crucial, a measurement of the conversion coefficients for the transitions in this energy range was performed. The conversion electron spectrum was obtained by a mini-orange electron spectrometer

TABLE 1

Gamma transitions in ^{153}Er observed in the $^{144}\text{Sm}(^{12}\text{C}, 3n)$ reaction at 62.3 MeV bombarding energy

E_γ ^{a)} (keV)	Relative intensity	Ang. dist. coeff. ^{b)}		Placement $E_i \rightarrow E_f$
		A_2/A_0	A_4/A_0	
194.3	162	-0.21(06)	0.15(08)	2945.5 $\rightarrow$ 2751.2
201.7	44 ^{c)}	-0.13(17)	0.32(25)	1699.0 $\rightarrow$ 1497.5
205.1	352	-0.23(06)	0.07(09)	970.7 $\rightarrow$ 765.6
284.7 } 284.7 }	30	0.28(23)	-0.03(36)	4779.0 $\rightarrow$ 4494.3
292.5	37	-0.01(19)	0.17(29)	4761.7 $\rightarrow$ 4477.0
299.4	1000	-0.05(02)	0.00(03)	4494.3 $\rightarrow$ 4201.8
340.2	776	0.15(02)	-0.05(02)	299.4 $\rightarrow$ 0
349.2	43	-0.25(13)	0.77(19)	2039.2 $\rightarrow$ 1699.0
356.3	52	-0.33(12)	-0.17(17)	5182.5 $\rightarrow$ 4833.3
363.1	127 ^{d)}	0.07(04)	0.11(06)	4833.3 $\rightarrow$ 4477.0
418.4	58	0.36(08)	-0.12(12)	3312.3 $\rightarrow$ 2949.2
530.2	134	0.24(04)	-0.08(06)	4477.0 $\rightarrow$ 4058.6
588.1	833	0.15(02)	-0.09(02)	2908.5 $\rightarrow$ 2378.3
653.2	506 ^{e)}	0.19(02)	-0.10(03)	1699.0 $\rightarrow$ 1110.9
692.8	108 ^{f)}	0.25(09)	-0.05(14)	2378.3 $\rightarrow$ 1725.1
696.6	59 ^{f)}	0.32(10)	-0.11(16)	4201.8 $\rightarrow$ 3509.0
712.0	502	0.00(02)	0.00(03)	2194.1 $\rightarrow$ 1497.5
731.9	145	0.14(05)	-0.03(08)	2751.2 $\rightarrow$ 2039.2
746.3	103	0.27(05)	-0.02(07)	1497.5 $\rightarrow$ 765.6
754.4	256	0.28(03)	-0.13(04)	4058.6 $\rightarrow$ 3312.3
757.8	120	0.25(05)	-0.13(07)	1725.1 $\rightarrow$ 970.7
765.6	585	0.27(02)	-0.15(03)	3509.0 $\rightarrow$ 2751.2
811.5	916	0.18(02)	-0.08(02)	765.6 $\rightarrow$ 0
910.0	147	0.28(04)	-0.08(07)	1110.9 $\rightarrow$ 299.4
				2949.2 $\rightarrow$ 2039.2

^{a)} Energy uncertainties are estimated from 0.1 keV for strong transitions up to 0.5 keV for weak transitions.^{b)} Only fitting errors are included.^{c)} Not corrected for contamination from ^{154}Er .^{d)} Not corrected for contamination from ^{153}Ho .^{e)} Not corrected for contamination from ^{150}Dy .^{f)} Problems with background from $\text{Ge}(n, n'\gamma)$.

with a cooled Si(Li) detector, and the γ -ray spectrum was simultaneously measured by a Ge(Li) detector. Both detectors were in coincidence with a filter consisting of 6 NaI(Tl) detectors. The experiment was done at a bombarding energy of 61.0 MeV. The conversion coefficients were normalized to the theoretical K-conversion coefficients ²¹⁾ for the known E2 transitions in ^{154}Er with energies of 601 and 625 keV. The results are presented in fig. 5. The 588.1, 754.4, 765.6 and 811.5 keV transitions are all clearly E2 transitions, in agreement with the conclusions drawn from the angular distribution measurements. From this measurement of the conversion

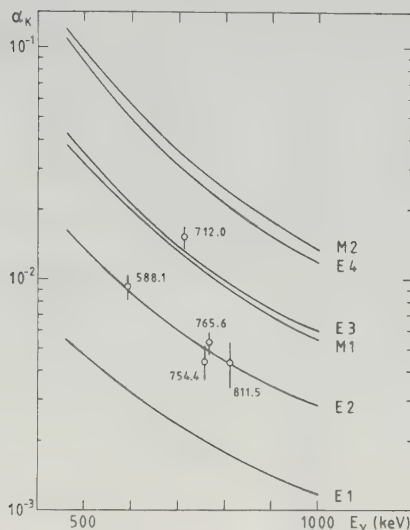


Fig. 5. Experimental conversion coefficients for transitions in Er ($Z = 68$). Full drawn curves are theoretical values from ref. ²¹).

coefficients it may be concluded that the 712.0 keV transition is either of E3 or M1 character[†].

The results of $\gamma\text{-}\gamma$ coincidence experiments are of decisive importance for the establishment of the level scheme. Two independent measurements were performed. In the first set-up four Ge(Li) detectors were placed at $\theta = 0^\circ, 55^\circ, 90^\circ$ and 90° . Using a ^{12}C beam of 63.0 MeV, coincident events between the detector mounted at 0° and any one of the remaining three detectors were recorded on magnetic tapes. Spectra from the 0° detector were afterwards constructed by setting gates on photo-peaks and appropriate background in the other detectors. The sorted spectra were added after background subtraction. The result of these analyses for transitions assigned to ^{153}Er are presented in table 2 and some particularly interesting coincidence spectra are displayed in figs. 6 and 7.

Another coincidence experiment at a bombarding energy of 65.0 MeV using 5 Ge(Li) detectors in Compton-suppression shields supplied no additional information.

[†] It can not be fully excluded that the 712.0 keV transition is an E1 transition with a (40%) M2 admixture. However, this requires an extreme retardation of the E1 strength, which seems very unlikely.

TABLE 2

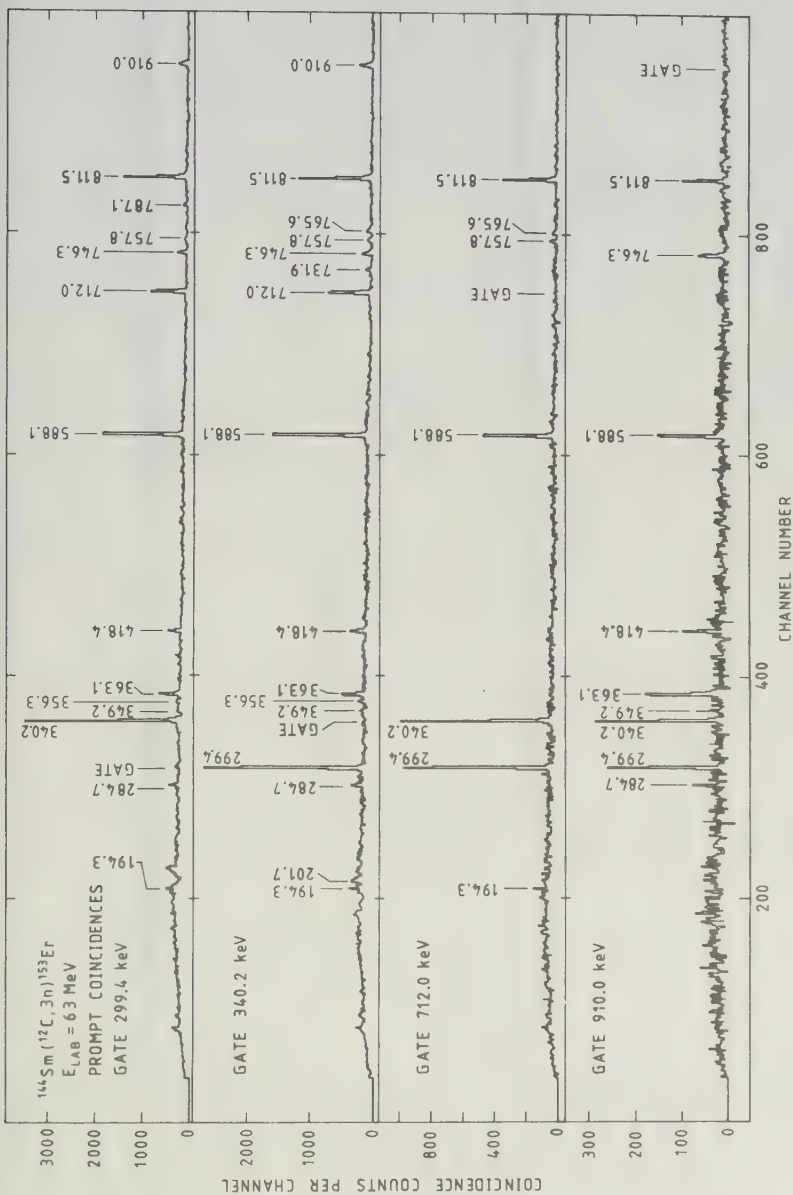
Coincidences in ^{153}Er from the reaction $^{144}\text{Sm}(^{12}\text{C}, 3n)$ at 63.0 MeV bombarding energy

Gate E (keV)	Coincident γ -rays (keV)
194.3	299.4, 340.2, 429 ^{a)} , 588.1, 659.3 ^{a)} , 712.0, 811.5
201.7	340.2, 456.0 ^{b)} , 507.2 ^{b)} , 560.6 ^{b)} , 601.3 ^{b)} , 625 ^{b)} , 669.1 ^{b)} , 731.9, 765.6
205.1	351.4 ^{a)} , 530.2, 653.2, 754.4, 765.6
284.7	292.5, 299.4, 340.2, 363.1, 418.4, 588.1, 746.3, 811.5, 910.0
292.5	284.7, 299.4, 318.6 ^{a)} , 340.2, 692.8, 757.8
299.4	194.3, 284.7, 340.2, 349.2, 356.3, 363.1, 418.4, 588.1, 712.0, 746.3, 757.8, 787.1 ^{c)} , 811.5, 910.0
340.2	194.3, 201.7, 284.7, 299.4, 349.2, 356.3, 363.1, 418.4, 588.1, 712.0, 731.9, 746.3, 757.8, 765.6, 811.5, 910.0
349.2	201.7, 299.4, 340.2, 356.3, 363.1, 418.4, 588.1, 746.3, 811.5, 910.0
356.3	299.4, 340.2, 349.2, 363.1, 418.4, 588.1, 746.3, 811.5, 910.0
363.1	284.7, 299.4, 340.2, 349.2, 356.3, 418.4, 532.5 ^{c)} , 557.0 ^{c)} , 588.1, 631.1 ^{c)} , 746.3, 811.5, 910.0, 912.9 ^{c)}
418.4	284.7, 299.4, 340.2, 349.2, 356.3, 363.1, 588.1, 746.3, 811.5, 910.0
530.2	205.1, 653.2, 754.4, 765.6
588.1	194.3, 284.7, 299.4, 340.2, 349.2, 356.3, 363.1, 418.4, 712.0, 746.3, 757.8, 787.1 ^{c)} , 811.5, 910.0
653.2	205.1, 393.9 ^{d)} , 403.6 ^{b)} , 411.1 ^{d)} , 530.2, 542.0 ^{b)} , 551.0 ^{b)} , 560.6 ^{b)} , 601.3 ^{b)} , 619.4 ^{b)} , 625.7 ^{b)} , 637.7 ^{b)} , 688.4 ^{b)} , 754.4, 765.6, 803.9 ^{d)}
692.8	292.5, 335.0 ^{a)} , 757.8
696.6	731.9, 765.6
712.0	194.3, 299.4, 340.2, 588.1, 757.8, 765.6, 811.5
731.9	201.7, 340.2, 696.6, 765.6
746.3	284.7, 299.4, 340.2, 349.2, 356.3, 363.1, 418.4, 588.1, 811.5, 910.0
754.4	205.1, 530.2, 653.2, 765.6
757.8	284.7, 292.5, 299.4, 340.2, 692.8
765.6	194.3, 201.7, 205.1, 340.2, 530.2, 653.2, 696.6, 754.4, 776.0 ^{a)} , 910.0
811.5	194.3, 284.7, 299.4, 340.2, 349.2, 356.3, 363.1, 418.4, 588.1, 712.0, 746.3, 757.8, 910.0
910.0	284.7, 299.4, 340.2, 349.2, 363.1, 418.4, 588.1, 746.3, 811.5

^{a)} Unassigned transitions. ^{b)} Transitions assigned to ^{154}Er .^{c)} Transitions assigned to ^{153}Ho . ^{d)} Transitions assigned to ^{150}Dy .^{e)} Transitions assigned to ^{153}Er but not placed in the level scheme.

3. The level scheme of ^{153}Er

The experimental information discussed above formed the basis for the construction of the level scheme, shown in fig. 8. Spin and parity of the ground state of ^{153}Er have not been measured. In conformity with adjacent $N = 85$ even- Z nuclei, we make the assumption $J^\pi = \frac{7}{2}^-$. Spin and parity assignments are then based on the angular distribution and conversion coefficient results on the assumption of stretched cascades and on systematics as discussed in sect. 4.

Fig. 6. Spectra of coincident γ -rays observed with gates at 299, 340, 712 and 910 keV.

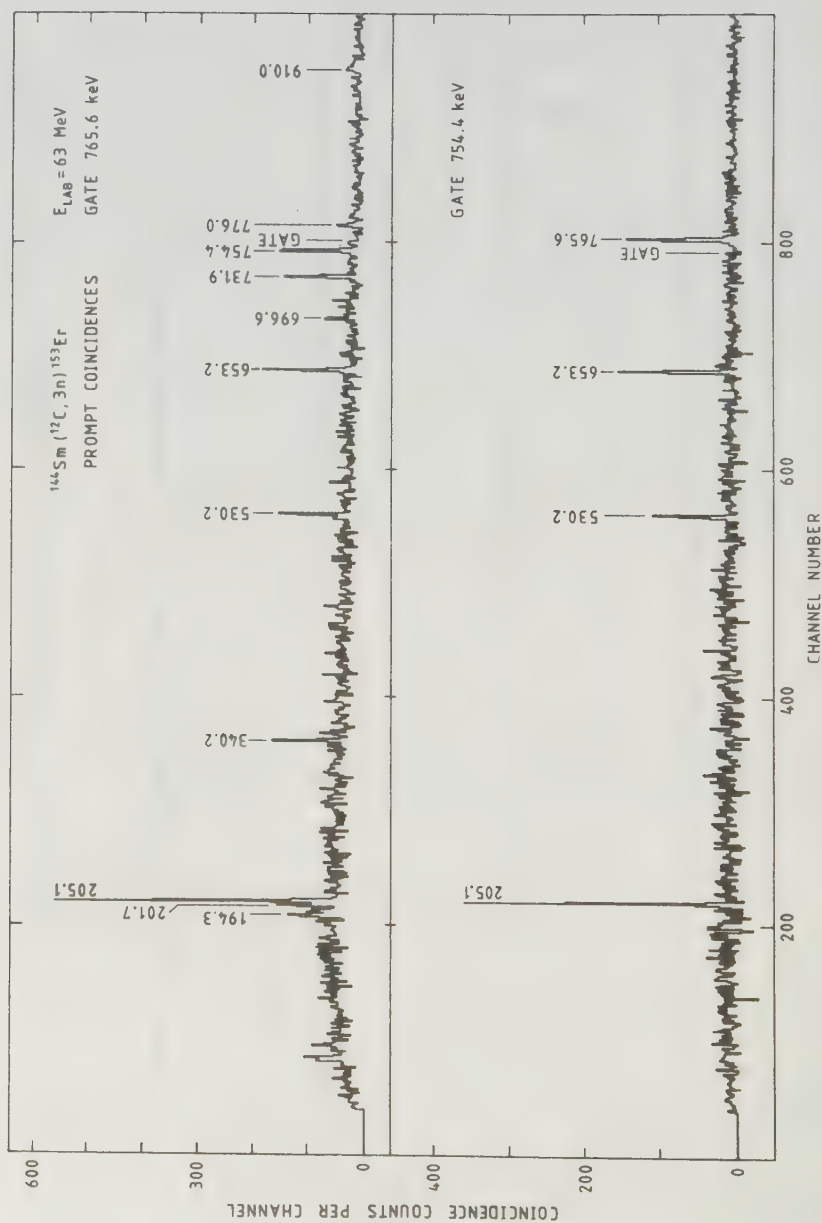


Fig. 7. Spectra of coincident γ -rays observed with gates at 765 and 754 keV. The appearance of the 194.3 and 776.0 keV transitions in the 765.6 keV gate has not been explained.

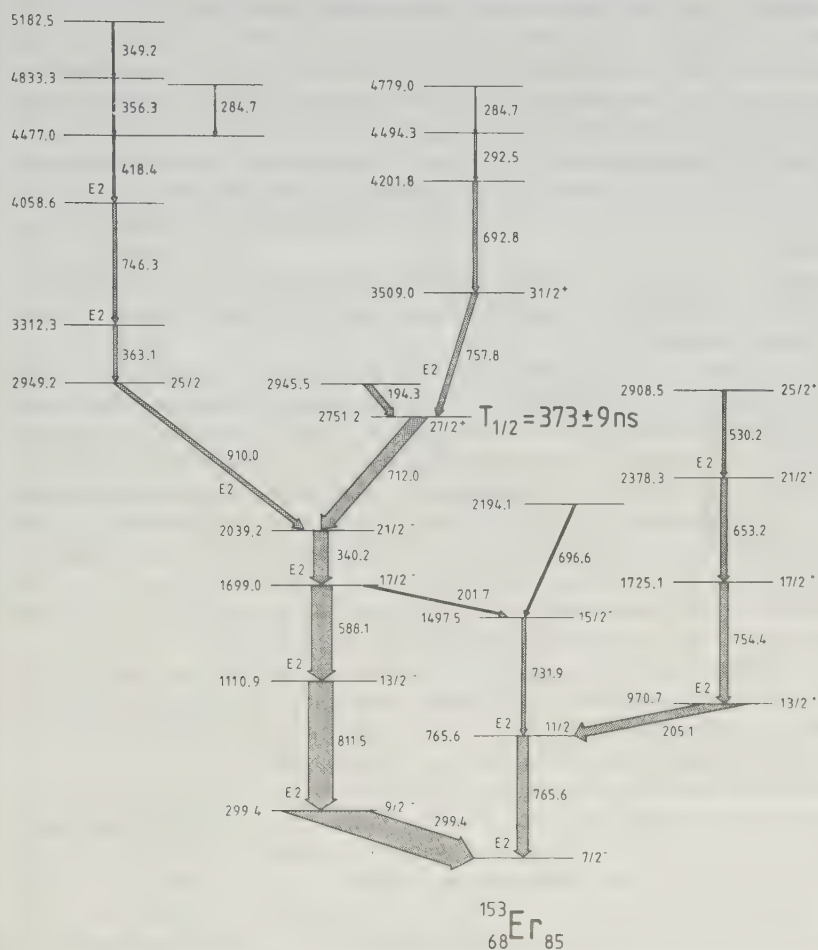


Fig. 8. Level scheme of ^{153}Er . The figure shows the decay pattern at 64.5 MeV. Spin and parity assignments are based on the present experimental results and comparisons with adjacent $N = 85$, even- Z nuclei.

The ordering of most of the transitions was deduced from the singles γ -ray intensities (cf. fig. 2). An additional check has been made by investigating the changes of the relative intensities of the γ -rays in the coincidence spectra obtained with gates set for the various members of the cascades. The placement of the 363.1 keV and 653.2 keV transitions was determined mainly from the coincidence data due to contaminating γ -rays in ^{153}Ho and ^{150}Dy , respectively, in the singles spectra.

A 284.7 keV γ -ray is undoubtedly in coincidence with all the transitions below the

4477.0 keV level in the cascade shown to the left in fig. 8. However, it also belongs to the cascade above the isomeric level, most probably feeding the 4494.3 keV level. If this was a single γ -ray the only way to explain its coincidence with the left cascade below 4477.0 keV would be a connecting transition of 17.3 keV. From coincidence data, we can conclude that most of the intensity of the 284.7 keV peak feeds into the cascade by-passing the isomer. It is very unlikely that the 17.3 keV transition would feed most of the intensity into the left cascade, because of the expected branching ratio of the 17.3 keV and the 292.5 keV transitions depopulating the 4494.3 keV level. Therefore there are most probably two transitions with almost the same energy.

A very weak 787.1 keV γ -ray, observed for some of the gates in the coincidence spectra, most probably belongs to the decay scheme of ^{153}Er , but its position could not be determined.

The existence of a strong delayed γ -ray cascade of five members depopulating a state at 2751 keV was early established ¹²⁾. There are many reasons for suggesting the 712.0 keV transition at the top of the cascade to be due to an isomeric transition: the absence of a prompt component in its time distribution, the isotropic angular distribution and the conversion coefficient suggesting an E3 character for the transition, in analogy with ^{149}Gd . The conversion coefficient is also compatible with an M1 transition. In that case, the long half-life would be difficult to understand, unless there is a low-energy isomeric transition, preceding the M1 transition. This possibility, which cannot be excluded, will be further discussed in sect. 4. The present data are, however, consistent without assuming such a close-lying doublet.

A ground-state band and a most probably positive-parity band, seen up to spin $\frac{25}{2}$, are fairly strongly populated at the present bombarding energies but hardly seen in experiments using higher energies ¹⁶⁾. The angular distribution of the 205.1 keV transition connecting these two bands has dipole character.

A well-developed band feeding into the isomeric cascade at 2039.2 keV and thus by-passing the isomeric state, takes us up to a level at 5182.5 keV which has actually been tentatively suggested ¹⁶⁾ to be an isomer with a half-life of 270 ns.

The delayed-coincidence experiment gave spectra showing the precursors. Besides transitions feeding the 40 ns isomer in ^{154}Er , three γ -rays of energies 194.3, 692.8 and 757.8 keV were seen. Traces of the 194.3 and 757.8 keV transitions are also seen in coincidence spectra with gates on members of the isomeric cascade. We therefore conclude that the 194.3 and 757.8 keV transitions most probably feed into the isomeric state. The 757.8 keV transition is at the bottom of a cascade of which four members are observed. Two very weak lines at 429 and 659.3 keV are observed in coincidence with the 194.3 keV transition, but it could not be determined whether they are in cascade or both feeding into the 2945.5 keV level. Therefore they were not included in the decay scheme.

4. Discussion

Some features of the $N = 85$, even- Z isotones are remarkably similar, as illustrated in fig. 9. However, there are also important differences. This situation most probably reflects the interplay between the single particle character of these neutron-deficient rare-earth nuclei with $A \approx 150$ as discussed in ref. ¹⁾ and the increasing importance of the collective properties ³⁾ as protons are added to or removed from the $Z = 64$ semi-closed shell. In the following we restrict ourselves to a discussion of the isotones with $Z \geq 64$.

Calculations with the deformed shell model ³⁾ have been performed. The potential energy surface is found to be very shallow for this and neighbouring nuclei with a preference towards an oblate shape ²²⁾. In the low spin region the minimum is close to a spherical shape with $\varepsilon_2 \approx -0.1$, but as the spin increases the deformation seems to increase somewhat, although the potential energy surface is still quite shallow.

In the spherical shell model the ground state of ^{153}Er has the configuration $\nu(f_{7/2})^3$ and spin and parity $\frac{7}{2}^-$. This assignment is supported by the very striking resemblance (cf. fig. 9) between the level structures at low energy of the neighbouring even- Z , $N = 85$ isotones which have $J^\pi = \frac{7}{2}^-$ for their ground states ²³⁾.

The $\frac{11}{2}^-$ and $\frac{15}{2}^-$ members of the $(f_{7/2})^3$ multiplet are observed in the present

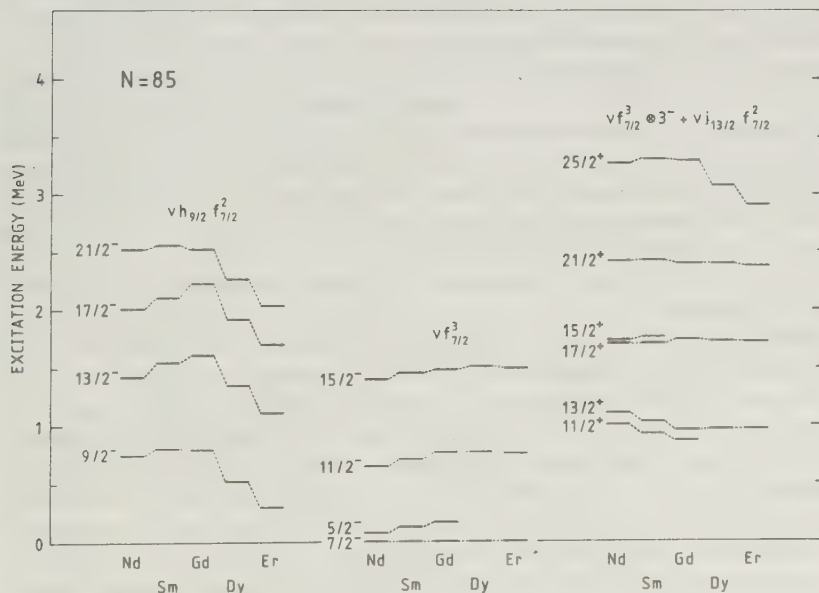


Fig. 9. Energy levels of even- Z isotones with $N = 85$ for different configurations.

experiment at energies that deviate from the corresponding ones in ^{151}Dy and ^{149}Gd by only a few percent. Other members of this multiplet are not observed here.

A $\frac{13}{2}^+$ state is found at 970.7 keV in ^{153}Er which is identified with the $\frac{13}{2}^+$ state at almost the same energy in the isotones ^{151}Dy and ^{149}Gd . Furthermore, the E2 transitions feeding the $\frac{13}{2}^+$ state have the same energies to within a few percent in the three isotones, constituting a multiplet which has been interpreted¹⁰⁾ in the case of ^{149}Gd as predominantly $(f_7)^3 \times 3^-$ excitations, although strongly mixed with $(f_7)^2 i_{7/2}$ single-particle states. The maximum spin of the $(f_7)^3 \times 3^-$ multiplet is $\frac{21}{2}$. The $\frac{25}{2}$ state at 2908.5 keV may then be interpreted as a more pure $(f_7)^2 i_{7/2}$ state with maximum spin alignment. The energies of the corresponding states in the two other isotones are here different. The $\frac{25}{2}$ to $\frac{21}{2}$ transition energies decrease considerably as the number of proton pairs increases.

A crucial point is the relative position of the deformed h_3 and f_7 neutron levels. In the spherical regime the j -shells are degenerate and f_7 lies below h_3 . For a deformed configuration the shells are split, and, in the oblate case, the substates of maximum K -quantum number come lowest. The f_7 shell would in that case be filled with three particles to form the ground state of ^{153}Er , two particles with $K = \frac{7}{2}$ and one particle with $K = \frac{5}{2}$ whereas the close-lying h_3 orbital is empty. At increasing oblate deformation the $(h_3, K = \frac{5}{2})$ state may even be found below the $(f_7, K = \frac{5}{2})$ state. Assuming that the ground state is $\frac{7}{2}^-$, a $\frac{9}{2}$ state is found in ^{153}Er at 299.4 keV and interpreted as the lowest member of a $\nu(f_7)^2 h_3$ multiplet. It is interesting to note that the corresponding state appears at lower energies as the proton number is increased over the $Z = 64$ shell (cf. fig. 9). This fact may in itself be an indication of a slightly oblate shape of the ground state of ^{153}Er .

The $\frac{9}{2}$, $\frac{13}{2}$, $\frac{17}{2}$, $\frac{21}{2}$ members of the $(f_7)^2 h_3$ multiplet are found with an energy spacing, that quite clearly carries a remembrance of the 0^+ , 2^+ , 4^+ and 6^+ sequence in the doubly even neighbouring nucleus ^{152}Er . This observation supports the interpretation of the one valence neutron being raised into the h_3 orbital and with the remaining f_7 neutron pair being excited through the sequence known from the doubly even nucleus. Very similar energy spacings within this multiplet are also observed for the other isotones.

Isomeric states are observed in adjacent $N = 85$ nuclides. Thus in ^{149}Gd a 6.0 ns isomer is reported¹⁰⁾ at 3387 keV while in ^{151}Dy the excitation energy of a 1.3 ns isomeric state is given as 2958 keV [ref. ¹¹⁾]. These isomers are classified for ^{149}Gd as mainly $\nu h_3((f_7)^2 \times 3^-)$ with $J^\pi = \frac{27}{2}^+$ and for ^{151}Dy as $\pi(h_{11/2})^2 \nu(f_7)^3$ with $J^\pi = \frac{27}{2}^-$. The isomer in ^{149}Gd decays partly by an E3 transition, whereas the isomer in ^{151}Dy decays through a fairly low-energy M1 transition, followed by an E2 transition. The present experiment does not support the existence of a low-energy transition deexciting the 373 ns isomer. We therefore suggest that the 2751 keV level, as the $\frac{27}{2}^+$ isomeric state, deexcites directly to the $\frac{21}{2}^- \nu(f_7)^2 h_3$ state by the 712.0 keV E3 transition, which can be identified as the analogue of the octupole transitions in neighbouring Gd nuclei. The isomeric states have about the same energy above the

$((f_{7/2})^2 h_{9/2})^2$ state for ¹⁴⁹Gd and ¹⁵³Er. The $B(E3)$ strength of the transition in ¹⁵³Er is 25 W.u., which amounts to about half of the values of the corresponding transitions in the Gd nuclei. The reason for the value in Er being lower is clearly seen: The octupole excitation is mainly formed out of proton particle hole states, where a $d_{5/2}$ single particle is promoted up to the $h_{9/2}$ shell. For the Gd nuclei ($Z = 64$) all the 12 substates of the $h_{9/2}$ configuration are available, whereas for Er ($Z = 68$) only 8 substates are still empty. Thus the Pauli principle does in zero order reduce the strength with a factor $(\frac{8}{12})^2 \approx 0.5$, in rough agreement with the data.

The 2751 keV isomeric state in ¹⁵³Er is thus interpreted as mainly due to a $h_{9/2} ((f_{7/2})^2 \times 3^-)$ coupling on the analogy of the situation in ¹⁴⁹Gd. From our calculations, assuming a moderately oblate deformation ($\epsilon_2 \approx -0.1$) the structure of the state would be

$$| \frac{27}{2}^+ \rangle = \nu(\alpha(f_{7/2} \times 3^-) + \beta i_{11/2}, K = \frac{1}{2}) \nu(f_{7/2} h_{9/2}, K = 7).$$

With this interpretation of the properties of the 373 ns isomeric state, it is an yrast state. It is then interesting to note that a cascade depopulating an upper isomer (¹³⁻¹⁶) by-passes the lower isomer. As the upper isomer most probably also is an yrast state it seems that we are here faced with a situation, where at least the main stream of the decay paths is leaving the yrast line. This situation is certainly worth a thorough study. The structure and the properties of the states above the lower isomer are at present very uncertain but at this energy the excitation of proton pairs out of the core must be taken into account.

The possibility of the 712.0 keV transition being of M1 character would necessarily involve the excitation of protons out of the core. The wave function of the isomeric state would then most probably contain a component $\pi((h_{9/2}, K = -\frac{9}{2})^{-1}(h_{9/2}, K = \frac{7}{2}))$. For $Z = 68$ the $h_{9/2}$ shell is occupied with 4 protons: in the oblate regime $K = \frac{1}{2}$ and $\frac{9}{2}$ are filled. The isomer would then decay by a low-energy E2 transition to the 2751 keV level. This decay pattern would be different from what is reported by Horn *et al.* ¹⁶), who suggest an isomeric M1 transition followed by an E2 transition (712 keV), in analogy with ¹⁵¹Dy. Although the existence of a close-lying doublet cannot be excluded, the present experimental results are better understood without its introduction.

It is interesting to study the variation in spin-parity assignments of the traps in $N = 85$ nuclei as the proton number is increased from $Z = 64$ to 66 and 68. Obviously, two different types of configurations compete in forming the trap state; a neutron excitation, of positive parity, involving the $i_{11/2}$ shell and the f_7 -octupole coupling, and a proton $h_{9/2}$ particle-hole excitation, of negative parity. In Gd the latter is not possible (assuming zero deformation) and the trap therefore must involve the former type. In Dy, however, both compete, and the proton configuration comes lowest. In Er, again, both compete but, here, the neutron excitation is most likely the winning partner. The reason for this is probably that the neutron excitation involves the $h_{9/2}(K = \frac{9}{2})$ orbital, and, looking at the lower-energy part of the level

scheme, the most striking difference between the $N = 85$ nuclei is the decreasing trend of the $\frac{5}{2}$ state as Z increases, as earlier discussed. This fact might cause the small energy shifts needed to change the character of the yrast trap.

The authors want to thank the Swedish and the Danish Natural Science Research Councils and the Nordic Committee for Accelerator Based Research for supporting this project.

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High-Spin Band Structure in ^{166}Yb

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Received October 6, 1980; accepted November 20, 1980

Abstract

High-spin states in ^{166}Yb have been studied via the $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction with 80 MeV ^{16}O ions from the NBI tandem accelerator. γ - γ coincidence data were accumulated with an array of four Ge(Li) and four NaI(Tl) detectors to favour high multiplicity events. Totally about 3×10^4 events were accumulated in the coincidence experiment. Measurements of the angular distribution of the γ -radiation and the conversion coefficients were furthermore performed. Four weakly populated side bands are observed besides the yrast cascade which is followed up to its 24^+ member. The ground state band has thus been identified to its 18^+ state, while the crossing Stockholm band becomes the yrast band from its 16^+ member. The S-band is established from its 12^+ state. The observed level energies and transition rates are well reproduced in calculations within the particle rotor model.

1. Introduction

In the mass region $A = 150$ – 170 the S-(Super or Stockholm) band [1] built upon aligned $(\nu_{13/2})^2$ orbits, usually crosses the ground state band (g.s.b.) around spin 14 and may cause back-bending, depending upon the interaction between the g.s. and S-band. The interpretation of the band structure and band crossings in rotational nuclei along the lines of Bohr and Mottelson [1] provides us with a means to compare experimental results with a microscopic theory and to extract quantities like the crossing frequency and the aligned angular momentum from the experimental data. The nucleus ^{166}Yb is of special interest, because *a priori* it would seem to be one of the best rotors which can be significantly populated at very high spins by (HI, xn) reactions. The identification of discrete lines in this work extends the information about the non-yrast bands from lighter and less rotational-like nuclei, and furthermore complements the gamma correlation work described elsewhere in these proceedings [2].

2. Experimental technique and results

States in ^{166}Yb were populated following the $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction at a beam energy of 80 MeV, the beams being provided by the NBI tandem accelerator. The experiments con-

sisted of γ -ray angular distribution, γ - γ coincidence and conversion electron coefficient measurements. The reaction yields at this bombarding energy, with an isotopically enriched, metallic target of ^{154}Sm sputtered to a thickness of 1.5 mg cm^{-2} onto a lead backing, were about 77% ^{166}Yb , 15% ^{165}Yb and 7% ^{167}Yb .

2.1. Singles γ -ray measurements

With the target at an angle of 45° relative to the beam direction two sets of singles γ -ray spectra were obtained at 5 different angles, one with a Ge(Li) detector at angles ranging between 58° and 148° and the other with a Ge(Li) detector in a Compton-suppression set-up at angles between 0° and 90° . One stationary Ge(Li) detector placed below the target served as the monitor. In spite of the low counting rate, the data for the weak transitions obtained with the anti-Compton set-up proved to be superior to those with the other detector due to the reduced background. Efficiency calibrations at various angles were performed with a radioactive ^{152}Eu source placed at the target position. A typical spectrum obtained with the anti-Compton set-up at 90° is shown in Fig. 1. Two sets of angular distribution coefficients were obtained, one for each detector, by fitting the peak intensities to the expression $W(\theta) = A_0 + A_2 P_2(\cos \theta) + A_4 P_4(\cos \theta)$, after normalizing them to the monitor yields and correcting for the dead times of the ADC:s and the variations of the relative efficiency at different angles. The results from the two detector set-ups are consistent. The results of the angular distribution measurements are summarised in Table I. The energy calibration was done by recording a singles γ -ray spectrum at 90° along with the spectrum from a ^{152}Eu source placed near the target.

2.2. γ - γ coincidence measurements

γ - γ coincidence measurements were performed with an array of four Ge(Li) detectors and four NaI(Tl) detectors. The gains of the amplifier of the Ge(Li) detectors were matched to be equal. Only those coincidence events were accumulated on magnetic tape for off-line analysis, for which two Ge(Li) counters in addition to at least one of the remaining Ge(Li) detectors or one of the NaI(Tl) detectors were triggered. In all, about 300 million pairs of events were accumulated. The tapes were sorted for all the possible combinations of pairs of detectors and the resulting spectra, after background subtrac-

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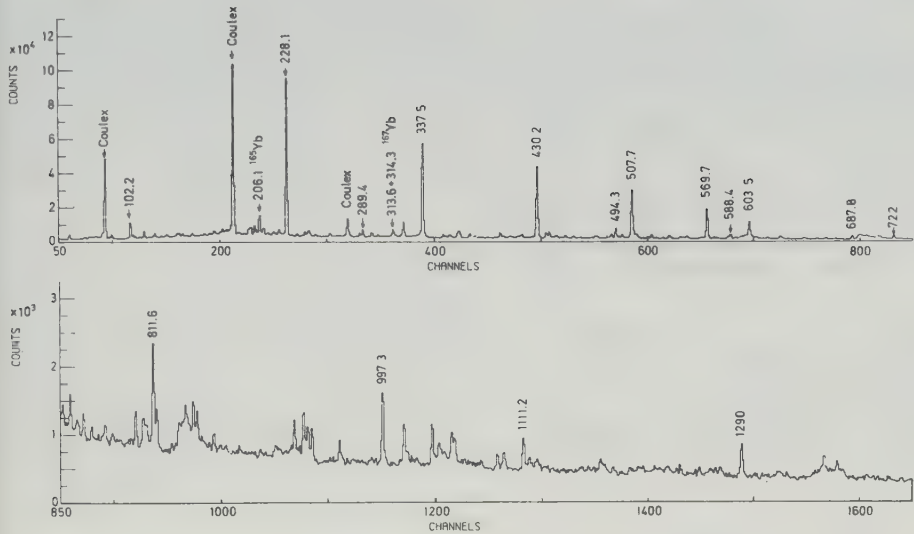


Fig. 1. Singles γ -ray spectrum at 90° to the beam direction, using an anti-Compton set-up, taken during bombardment of a ^{154}Sm target with 80 MeV ^{16}O .

Table I. The energies, intensities and angular distribution coefficients for the transitions assigned to ^{166}Yb following the $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction at 80 MeV

E_γ^a (keV)	Intensity ^b	Ang. dist. coeff. ^c		$I_i^{\pi d} \rightarrow I_f^{\pi d}$
		A_2/A_0	A_4/A_0	
102.2		0.27(03)	-0.06(03)	$2^+ \rightarrow 0^+$
114				$8^- \rightarrow 7^-$
152				$10^- \rightarrow 9^-$
206 ^e	16	0.21(07)	-0.05(08)	$8^- \rightarrow 6^-$
228.1	987	0.30(03)	-0.09(03)	$4^+ \rightarrow 2^+$
248 ^e	8			$6^- \rightarrow (4^-)$
274 ^e	Weak			$(7^-) \rightarrow (7^-)$
276 ^e	Weak			$(7^-) \rightarrow (6^-)$
289 ^e				$(4^-) \rightarrow 5^+$
289.4	55	0.30(02)	-0.10(02)	$10^- \rightarrow 8^-$
301.4	14	0.42(05)	0.02(05)	$(8^-) \rightarrow (6^-)$
337.5	1000	0.32(03)	-0.11(03)	$6^+ \rightarrow 4^+$
341	Weak			$(10^-) \rightarrow 9^+$
354.4	28	0.28(03)	-0.03(04)	$(10^-) \rightarrow (8^-)$
356 ^e	16			$12^+ \rightarrow 12^+$
366 ^e	5			$14^+ \rightarrow 12^+$
367.6 ^e	65	0.29(02)	-0.15(02)	$12^- \rightarrow 10^-$
368 ^e				$(7^-) \rightarrow 6^-$
375.8	37	0.27(02)	-0.12(03)	$16^+ \rightarrow 14^+$
400.4	51	0.34(03)	-0.10(03)	$(12^-) \rightarrow (10^-)$
403 ^e	17			$17^- \rightarrow 16^-$
430.2	856	0.31(03)	-0.13(03)	$8^- \rightarrow 6^-$
432 ^e	Weak			$(8^-) \rightarrow 7^+$
437.6	63	0.27(03)	-0.08(03)	$14^- \rightarrow 12^-$
445.8 ^e	33	0.14(09)	-0.02(07)	$13^- \rightarrow 11^-$
446 ^e				$9^- \rightarrow 7^+$
459.4	27	0.36(05)	-0.19(05)	$(14^-) \rightarrow (12^-)$
490.8	43	0.32(06)	-0.07(09)	$15^- \rightarrow 13^-$
494.3	128	0.35(010)	-0.09(01)	$16^+ \rightarrow 14^+$
496.7	22	0.38(04)	-0.18(05)	$(11^-) \rightarrow 9^+$

Table I. (continued)

E_γ^a (keV)	Intensity ^b	Ang. dist. coeff. ^c		$I_i^{\pi d} \rightarrow I_f^{\pi d}$
		A_2/A_0	A_4/A_0	
499.5	45	0.33(03)	-0.13(03)	$16^- \rightarrow 14^-$
507.7	645	0.32(08)	-0.09(01)	$10^+ \rightarrow 8^+$
508 ^e				$(6^-) \rightarrow 5^+$
509 ^e	160	0.23(03)	-0.11(03)	$18^+ \rightarrow 16^+$
527.5	14	0.26(07)	-0.01(11)	$(16^-) \rightarrow (14^-)$
538 ^e	19	-0.26(24)	-0.16(25)	$6^- \rightarrow 5^+$
538.2 ^e	35	0.47(13)	0.04(14)	$17^- \rightarrow 15^-$
550 ^e	15	0.22(04)	0.03(07)	$13^+ \rightarrow 11^+$
552.8	32	0.20(05)	-0.03(08)	$18^- \rightarrow 16^-$
569.7	480	0.33(03)	-0.11(03)	$12^+ \rightarrow 10^+$
575.1	17	-0.30(18)	0.15(17)	$15^- \rightarrow 14^+$
586.2 ^e	30	0.22(07)	0.34(09)	$19^- \rightarrow 17^-$
588.4	69	0.36(05)	-0.02(08)	$20^+ \rightarrow 18^+$
592 ^e	14	0.27(17)	-0.07(22)	$16^- \rightarrow 14^+$
592 ^e	10			$(18^-) \rightarrow (16^-)$
600.1	25	0.25(12)	0.05(13)	$20^- \rightarrow 18^-$
603.5	250	0.31(02)	-0.13(02)	$14^+ \rightarrow 12^+$
629 ^e	24	0.29(03)	-0.05(07)	$(6^+) \rightarrow 5^+$
630 ^e				$21^- \rightarrow 19^-$
649 ^e	10			$22^- \rightarrow 20^-$
649 ^e	Weak			$(20^-) \rightarrow (18^-)$
660 ^e	7			$5^+ \rightarrow 6^+$
667	25	Doppler broadened		$22^+ \rightarrow 20^+$
674 ^e	13	0.13(09)	-0.33(09)	$23^- \rightarrow 21^-$
687.8	45	-0.21(02)	0.10(03)	$13^+ \rightarrow 12^+$
701				$18^- \rightarrow 16^-$
709 ^f	4			$3^+ \rightarrow 4^+$
710.3	39	0.34(03)	-0.02(05)	$16^+ \rightarrow 14^+$
722.0	69	0.35(01)	-0.05(02)	$14^+ \rightarrow 12^+$
739		Doppler broadened		$24^+ \rightarrow 22^+$

Table I. (continued)

E_{γ}^a (keV)	Intensity ^b	Ang. dist. coeff. ^c		$I_{\gamma}^{d \rightarrow I_{\gamma}^{d}}$
		A_2/A_0	A_4/A_0	
811.6	39	-0.15(07)	0.01(06)	$11^- \rightarrow 10^+$
830 ^f	22			$2^+ \rightarrow 2^+$
860	10			$(7^-) \rightarrow 8^+$
925.6	15	0.27(05)	-0.16(07)	$12^{++} \rightarrow 10^+$
932 ^f	21			$2^+ \rightarrow 0^+$
936 ^f	16			$3^+ \rightarrow 2^+$
997.3	38	-0.19(03)	0.15(07)	$5^+ \rightarrow 4^+$
1037	22	-0.31(06)	0.05(07)	$7^+ \rightarrow 6^+$
1053	16	-0.31(07)	0.03(08)	$9^+ \rightarrow 8^+$
1111.2	19	-0.22(04)	0.04(05)	$9^- \rightarrow 8^+$
1122	8	-0.19(04)	0.06(04)	$(5^-) \rightarrow 6^+$
1290	25			$(7^-) \rightarrow 6^+$
1460 ^e				$(5^-) \rightarrow 4^+$

^a Energy uncertainties are 0.2 keV for strong transitions (rel. int. > 50), rising to 0.5 keV for weaker transitions.

^b Intensities are given relative to the $6^+ \rightarrow 4^+$ g.s.b. transition.

^c Only fitting errors are given.

^d Assignments in brackets are tentative.

^e Weak or doublet. Intensities wherever given for individual transitions, are based on the coincidence data, uncorrected for the angular correlation effects.

^f Lines known from the decay of ^{146}Lu . Assignments are based on the observed branching ratios.

tion, were added together. Examples of coincidence spectra are shown in Fig. 2. In a similar coincidence run for studying the ^{167}Yb nucleus with an 80 MeV ^{17}O beam, the yield of ^{166}Yb was about 50% with no observable yield found for ^{165}Yb . As many transitions in ^{165}Yb have the same or nearly the same energy as those in ^{166}Yb , the data from the latter experiment helped to remove ambiguities concerning many weak transitions and to confirm the level scheme of ^{166}Yb .

2.3. Conversion coefficient measurements

In order to ascertain the multipolarities of the transitions, the conversion electron spectrum was obtained at 55° with a solenoid transporter and a cooled Si(Li) detector. The electron intensities were recorded in the range from about 600 keV to about 1200 keV as this region contained most of the interband transitions. A γ -ray-spectrum was also recorded simultaneously at -55° . The conversion coefficients were normalized to the $\alpha_K(E2)$ values of the 603, 710 and 722 keV transitions. The results of the conversion coefficient measurements have led to the assignment of negative parity of two side bands.

3. Construction of the level scheme

The yrast sequence of levels in ^{166}Yb was earlier known up to spin 20^+ . Many low-lying levels up to an excitation energy of 2.43 MeV are known from the radioactive decay studies [3] of ^{166}Lu . The level scheme of ^{166}Yb , as deduced from the present work, is presented in Fig. 3. Previously known levels, not seen in this work, are not included in the figure. The spin and parity assignments are based on the angular distribution and conversion coefficient measurements with frequent reference to previous measurements. All the transitions within a band are found to be of stretched E2 character. The ordering of the transitions within a band is based on their coincidence relationships and their relative intensities.

3.1. The ground state and S-bands

The yrast sequence of levels has been extended up to a spin of 24^+ and the g.s.b. to a spin of 18^+ . Although the 667 and 739 keV lines, depopulating the 22^+ and the 24^+ levels, respectively, show considerable Doppler broadening, their angular anisotropies are well enough determined and have the same magnitude as expected for stretched E2 transitions high up in a

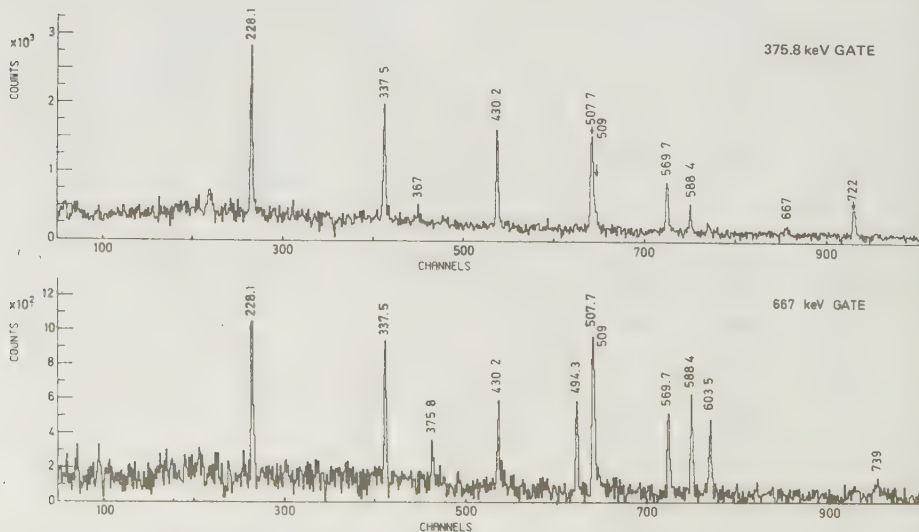


Fig. 2. Ge(Li) $\gamma\gamma$ coincidence spectra (background - subtracted) observed following the $^{144}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction at 80 MeV.

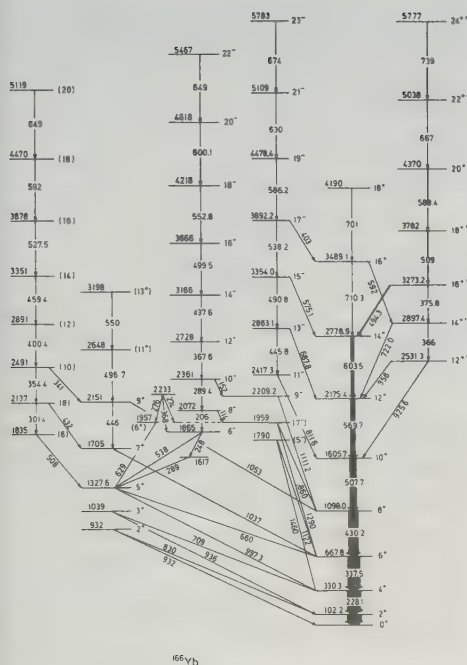


Fig. 3. Level scheme of ^{166}Yb showing states populated by the $^{154}\text{Sm}(^{14}\text{O}, 4n)^{166}\text{Yb}$ reaction.

cascade, and thereby justify their assignments. The 356 keV transition from the 12^- to the 12^+ state could only be inferred from the coincidence data. Its intensity, the angular distribution coefficients and hence the M1/E2 mixing ratio could not be determined due to the presence of a contaminant line from the radioactive decay of the reaction products. The intensity of the 592 keV 16^- to 14^- state transition could only be inferred from the coincidence data due to the presence of another transition having nearly the same energy.

3.2. The odd-spin negative parity band

One band with odd-spin and negative parity has been identified. The 11^- member of this band and the higher lying members are joined by a cascade of stretched quadrupole transitions and connected to the g.s.b. by four interband transitions. The measured K -conversion coefficient of the 688 keV transition confirms the negative parity assignment of this band. The intensity ratios of the intraband transitions to the interband transitions to the g.s.b. decrease going down the band. The intraband transitions among the 5^- , 7^- , 9^- and the 11^- states at 1790, 1959, 2209 and 2417 keV are too weak to be detected in the coincidence work. The 5^- and 7^- states are known from the work of de Boer et al. [3]. The stretched E1 character of the transition from the 9^- state to the 8^- member of the g.s.b. is established from angular distribution and conversion coefficient measurements.

3.3. The even-spin negative parity band

The level at 1865 keV, which lies at the bottom of the even-spin negative parity band, has been observed in the radioactive decay of ^{166}Lu [3] and assigned a spin and parity of 6^- . The regularity and the stretched E2 character of the cascade transitions populating this level justify the classification of this cascade as a band. Furthermore, the state 10^- at 2361 keV decays by an intense, mixed transition to the level at 2209 keV, which is assigned as having spin and parity 9^- in this study. This mixed transition is assumed to be of the M1/E2 type. Multipole admixture of higher order than quadrupole would require the level at 2361 keV to be an isomer with a lifetime of the order of microseconds.

3.4. The γ -vibrational band

Several members of the γ -vibrational band have been observed earlier in the radioactive decay of ^{166}Lu [3]. The 5^+ member of this band is populated rather strongly in the present study and angular distribution and the conversion electron data confirm the 5^+ assignment. The 2_2^+ and 3_2^+ levels are populated very weakly and we infer their presence in this study from the observed branching ratios of the decays of these levels. The 7^+ level at 1705 keV has been found to decay by a stretched M1 transition to the 6^+ state of the g.s.b. It is to be noted that this level is not the same as the 7^+ level found earlier [3]. The assignment of the higher lying members of this band is only tentative and is based upon the observed decay properties of these levels, the systematic variation of the level differences and the similarity to the $N = 96$ isotope ^{164}Er .

3.5. An unassigned rotational band and further levels

A band of levels of unknown spins and parity and built on the 1835 keV state is observed in the present study. This band is connected by means of three weak interband transitions to the proposed γ -vibrational band, and the energies of these transitions are too close to strong g.s.b. transitions to make a determination of their multipole character possible in the present experiment. The tentatively suggested spins and negative parity are based on the observation of a similar band in ^{164}Er starting in that case with spin (8) at an excitation energy of 2091 keV.

The levels at 1617, 1957 and 2233 keV (cf. Fig. 3) are known from the work of de Boer et al. [3]. Our identification of these levels is based solely on the observation of some transitions originating from these levels in our coincidence spectra. Only these transitions are shown in Fig. 3 and other decay modes of these levels, not established in the present study, are excluded from the figure.

4. Theoretical considerations

A crossing of two bands is sometimes referred to as virtual or real, depending on whether or not an interaction between the two bands is likely to deflect a gamma cascade from one band to another. The real crossing known in the deformed rare-earth nuclei all occur between bands which do not interact because of different signature or parity. The crossings between the g.s. and S-bands, on the other hand, are generally virtual and an yrast cascade tends to stay yrast. However, it is illustrated by the case of ^{166}Yb that even when the interaction between the bands is not forbidden, there may be situations when the nucleus prefers to follow a band of given structure rather than

the trajectory of lowest energy. In Section 4.1 the general conditions for such behaviour are formulated in terms of the band parameters. In Section 4.2 it is pointed out that the different cascade patterns in the two $N = 96$ isotones ^{164}Er and ^{166}Yb arise naturally in particle-rotor calculations based on the notion of $(\nu_{13/2})^2$ bands crossing the ground band. Section 4.3 contains a phenomenological analysis in terms of cranking model quantities for the positive and negative parity bands shown in Fig. 3.

4.1. Two-band analysis

A schematic model can be used to derive the conditions when a crossing between two weakly interacting bands is mainly virtual or mainly real. The energies of the two unperturbed bands as functions of the spin I are written

$$E = A_i(I - J_i)^2 + E_i^0, \quad i = 1, 2$$

They cross at a spin I_c . The difference $J_2 - J_1$ between the aligned spins is denoted j . Perturbed bands are obtained by diagonalizing a two by two matrix with an off-diagonal matrix element V . It is then straightforward to find the perturbed energies and the relative transition rates. The branching ratio of the transition rates from the lowest state of spin I to the upper and lower states of spin $(I - 2)$ are, in two special cases

$$\frac{T(I_c \rightarrow I_c - 2)}{T(I_c \rightarrow (I_c - 2)')} = \left[\frac{1}{1 - (j/I_c)} \right]^5 + O(V)$$

and

$$\frac{T(I_c + 1 \rightarrow I_c - 1)}{T(I_c + 1 \rightarrow (I_c - 1)')} = \frac{V}{A_j} \left[\frac{1 - \frac{1}{2}(j/I_c)}{1 - (j/I_c)} \right]^5 + O(V^2)$$

respectively. In the first case the bands cross at one of the discrete spins where states exist, and it is seen that the yrast cascade tends to remain yrast. In the second case, where the bands cross in between the discrete states, the yrast cascade tends to leave the yrast line if V is sufficiently small. For given A and j this situation is clearly favoured by a large spin I_c .

A two-band analysis along the lines of [4] for the energy levels of ^{164}Er and ^{166}Yb is described in Section 4.3 below. It gives $I_c \sim 16$ in the former nucleus and $I_c \sim 15$ in the latter which thus accounts for the observed difference in the gamma cascade of the two nuclei. Other parameters obtained from the two-band analysis are the interaction V between the two unperturbed bands, and the inertia parameters. The branching ratios of the decays of the g.s. and the S-band suggest an interaction V of the order of 45–50 keV.

4.2. Particle-rotor analysis

It has recently been shown [5, 6] that the many-BCS-quasiparticle plus rotor Hamiltonian within a $(i_{13/2})^2$ valence space can be adjusted to give an accurate description of the energies along the g.s. and S-bands of ^{164}Er and ^{166}Yb . If the energies are correct it is expected that the calculation also accounts for branching ratios, and in particular the observed differences between the two nuclei in this respect. For ^{166}Yb the adjustable parameters [5] ($\theta_0 = 35.463 \text{ MeV}^{-1}$, $C = 0.0039308 \text{ MeV}^3$, $\lambda = 0.0545 \text{ MeV}$ above ϵ_{S2} and $\Delta = 0.669952 \text{ MeV}$) were fitted in [5] to the yrast levels of spin $I = 0-20$, so the energies of all non-yrast levels, and, furthermore, the branching ratios, can be regarded as predictions of the model. A calculated branching of the yrast cascade at $I = 16$ has been reported earlier [7].

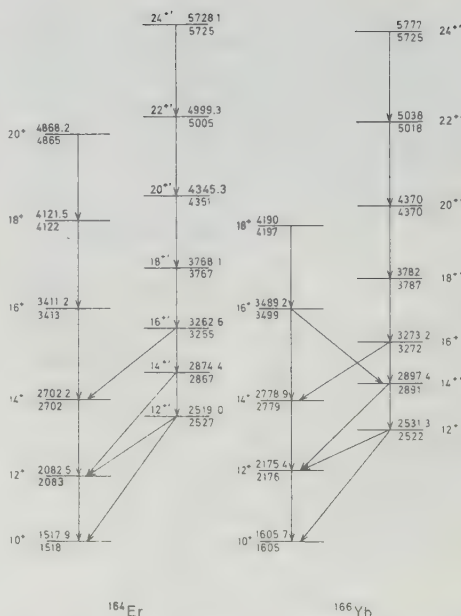


Fig. 4. Comparison of the theoretical and experimental level energies for the g.s. and S-bands of ^{164}Er and ^{166}Yb . The calculated energies are shown below the experimental values.

A comparison between results of the model calculations and experiments is given for the two nuclei in Fig. 4 and Table II. The energies of the non-yrast levels in ^{166}Yb are of course not quite as well reproduced as in ^{164}Er , where levels from the high-spin continuation of the g.s.-band and the low-spin continuation of the S-band were included in the parameter fitting procedure. Nevertheless, the calculation is sufficiently accurate to describe the branching of the electromagnetic decay, cf. Table III. The transitions following the unperturbed bands through the crossing are indeed significantly stronger for ^{166}Yb than for ^{164}Er . Thus the transition from 16^+ to 14^+ has been seen in the ^{166}Yb case but not in ^{164}Er . A decay branch from the 12^+ level to the 12^+ level as well as to the 10^+ level is measured in ^{166}Yb . The 12^+ to 12^+ transition is of particular interest because, according to the calculation, it is an almost pure M1 from the S-band to the g.s.-band. The parameters employed here for calculating the electromagnetic transition rates are $Q = 7b$, $e^{\text{eff}} = e$, $g_s^{\text{eff}} = 0.6g_s^{\text{free}}$, $g_l = 0$ and $g_R = Z/A$. A complication which should be noted is that the observed 12^+ level comes 9 keV above the calculated one, and just as in ^{164}Er , this may indicate an admixture of the 12^+ level from the gamma band [8].

4.3. Cranking model analysis

The alignment plots [9] for the various bands are shown in Fig. 5. The g.s. and the other bands except the S-band, are fitted with the parameters [9] $J_0 = 29 \text{ MeV}^{-1} \hbar^2$ and $J_1 = 136 \text{ MeV}^{-3} \hbar^4$. The corresponding parameters for the S-band have been adjusted to give a constant value of i_x above the backbend

Table II. Comparison of the theoretical and experimental level energies for the g.s. and S-bands of ^{164}Er and ^{166}Yb . The calculated energies are shown in brackets alongside the experimental values.

^{164}Er			^{166}Yb		
	g.s.b.	S-band		g.s.b.	S-band
0 ⁺	0 (0)		0 (0)		
2 ⁺	91.3 (91.5)		102.2 (101.9)		
4 ⁺	299.4 (299.9)		330.3 (330.1)		
6 ⁺	614.3 (615.1)		667.8 (667.8)		
8 ⁺	1024.5 (1025.0)		1098.0 (1097.8)		
10 ⁺	1517.9 (1518.0)		1605.7 (1605.3)		
12 ⁺	2082.5 (2082.7)	2519.0 (2527.3)	2175.4 (2176.4)		2531.3 (2522.1)
14 ⁺	2702.2 (2702.4)	2874.4 (2866.6)	2778.9 (2779.3)		2897.4 (2890.5)
16 ⁺	3411.2 (3415.0)	3262.6 (3255.0)	3489.2 (3499.1)		3273.2 (3271.9)
18 ⁺	4121.5 (4122.2)	3768.1 (3767.1)	4190 (4196.6)		3782 (3786.6)
20 ⁺	4868.2 (4865.5)	4345.3 (4350.7)			4370 (4370.0)
22 ⁺		4999.3 (5005.0)			5038 (5018.0)
24 ⁺		5728.1 (5724.9)			5777 (5725.0)

and are $J_0 = 33.5 \text{ MeV}^{-1}\hbar^2$ and $J_1 = 62.5 \text{ MeV}^{-3}\hbar^4$. The fact that the same values of the moment of inertia parameters generally do not give constant alignment values both below and above the backband has been discussed by Bengtsson [10] and is probably due to the changes in the core associated with the backbending effect. The g.s. and S-bands show up with nearly constant alignments after correction for their mutual interaction, which is assumed to be constant and equal to 50 keV. The point corresponding to the $18^+ \rightarrow 16^+$ g.s.b. transition shows unbending, which is due to a crossing with the S'-band in the particle-rotor calculation.

The experimental Routhians are shown in Fig. 6. The S-band Routhian crosses that of the g.s.b. at $\hbar\omega = 0.28 \text{ MeV}$. The odd-spin odd parity band shows regular behaviour only above spin 11⁺. This band and the even-spin negative parity band built on the 6⁺ state at 1865 keV could be the two lowest bands with $\alpha = 1$ and 0 respectively, built on the neutron levels labelled [642 $\frac{1}{2}$] and [523 $\frac{1}{2}$] at zero frequency [9].

The extrapolated experimental Routhians for these bands cross the g.s. band at $\hbar\omega \approx 0.36 \text{ MeV}$. No concrete assignments have been made for the band with the band head at 1835 keV. The spin of the band head is probably 6. If this is the case, then this band could be the other $\alpha = 0$ even-spin negative parity

band based on the same neutron quasiparticle configuration as mentioned above. It may be noted, however, that the lowest identified member of a similar band in $N = 96$ isotope ^{164}Er has been assigned a spin (8) and has been suggested [9] to belong to the neutron configuration [642 $\frac{1}{2}$] [505 $\frac{1}{2}$] $K = 8$.

5. Conclusions

Judging by the first few states of the g.s. bands, the nucleus $^{166}\text{Yb}_{96}$ is more appropriately classified as a stable deformed rotational nucleus than the more neutron-deficient rare-earth isotopes. Previously the only high-spin levels known were the yrast levels up to spin 20 [11]. In the present work six bands are identified, up to spin 24 on the yrast line and up to 23 in one of the side bands, thereby extending the systematics of high-spin band structure into the region of well-deformed nuclei. Many of the states were also populated and assigned similar spins and parities in a parallel study of the $^{162}\text{Dy}(^7\text{Be}, 5n)^{166}\text{Yb}$ reaction at Brookhaven [12]. The positive-parity bands are presumably aligned neutron ($i_{13/2}$) configurations and the negative-parity

Table III. Comparison of the theoretical and experimental $B(E2)$ and $B(M1)$ ratios for g.s. and S-bands of ^{164}Er and ^{166}Yb

	^{166}Yb		^{164}Er	
	th.	exp.	th.	exp.
$B(E2, 16^+ \rightarrow 14^+)$	1:1.3	1:0.9	1:0.6	—
$B(E2, 16^{++} \rightarrow 14^{++})$	1:1.2	1:0.9	1:0.5	1:0.4
$B(E2, 16^{++} \rightarrow 14^{++})$	5.2:1	—	35:1	—
$B(E2, 14^{++} \rightarrow 12^{++})$	4.4:1	2.1:1	24:1	22:1
$B(E2, 12^{++} \rightarrow 10^{++})$	2000:1	1600:1	1200:1	1250:1

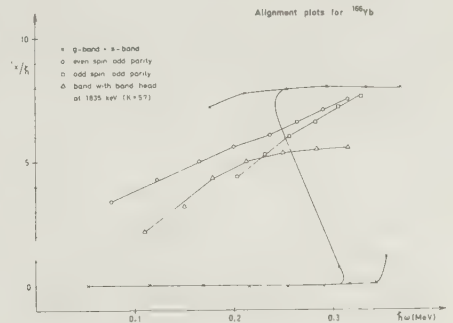


Fig. 5. Plot of the alignment vs. rotational frequency for the various bands in ^{166}Yb . The g.s. and the other bands except the S-band are fitted with the parameters [9] $J_0 = 29 \text{ MeV}^{-1}\hbar^2$ and $J_1 = 136 \text{ MeV}^{-3}\hbar^4$. The corresponding parameters for the S-band have been adjusted to give a constant value of I_x above the backbending and are $J_0 = 33.5 \text{ MeV}^{-1}\hbar^2$ and $J_1 = 62.5 \text{ MeV}^{-3}\hbar^4$.

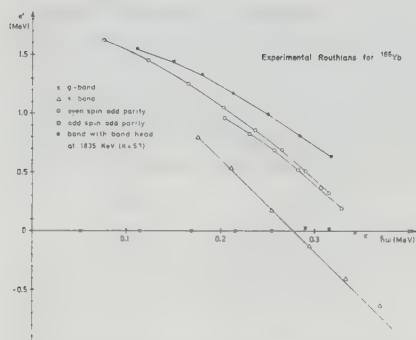


Fig. 6. Experimental Routhians for the various bands in ^{166}Yb .

bands could be neutron $(i_{13/2})(h_{11/2})$ configurations [9]. The VMI parameters, Routhians and values for the aligned angular momentum are extracted from the data. A gamma correlation experiment [13] has also been made recently, which reaches the very high-spin states in the isotopes around ^{166}Yb , and the information obtained in the present work about the detailed spectroscopy up to spins above 20 should be a valuable aid in the interpretation of the results [2, 14].

The crossing between the g.s. and S-bands of ^{166}Yb has a special feature. It is the first known case of a crossing between two interacting bands in deformed rare-earth nuclei where a significant fraction of the cascade intensity leaves the trajectory of the lowest energy in order to follow an unperturbed band characterized by intrinsic structure. The mechanism is a small interaction combined with a band crossing spin in between the even integer values where there are physical states. Heating of the nucleus by this mechanism may occur more frequently for

band crossings at higher spins. A number of interband transitions are observed in the present case at and just below the crossing, which provide more of a test for theory than the data on other backbending rare-earth nuclei. The levels and the M1 and E2 transitions matrix elements obtained from an $(i_{13/2})^2$ plus rotor calculation, made before the experiment and fitted to the energies along the yrast line, turn out to be consistent in detail with the observed energies and intensities.

Acknowledgements

We wish to express our sincere thanks to the Nordic Committee for Acceleratorbased Research for financial support.

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NEAR-YRAST SPECTROSCOPY OF $^{165-167}\text{Yb}$

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Received 10 December 1981

Abstract: The lowest $(\pi, \alpha) = (+, +)$, $(+, -)$ and $(-, +)$ rotational sequences in $^{165,167}\text{Yb}$ as well as the lowest $(-, -)$ sequence in ^{165}Yb have been established to high spins. The single-quasineutron portions of these sequences are used to construct two- and three-quasineutron states which are compared to the corresponding configurations in $^{165,166,167}\text{Yb}$. Such a comparison indicates that the residual interactions between two quasineutrons are nearly independent of $\hbar\omega$ and configuration (for those studied), are attractive and are equal to about 300 keV. For three-quasineutron configurations an $\hbar\omega$ dependence is observed in the residual interaction, which can be interpreted as a reduction in alignment for the three-quasineutron configurations, a result of reduced pairing. Difficulties in reproducing the signature-dependent energy-splitting and band-crossing frequencies in the positive-parity decay sequence are not completely understood. The signature dependence of the interband-intraband branching ratios as well as of the interband M1/E2 mixing ratios provide an experimental justification of the signature dependence of $B(M1)$ transition rates recently suggested by Hamamoto.

NUCLEAR REACTIONS $^{152,154}\text{Sm}(^{17}\text{O}, xn)$, $(^{18}\text{O}, xn)$, $E = 80\text{--}84$ MeV; measured $\gamma\gamma$ -coin, $\gamma(\theta)$, ICC following 4, 5 neutron emission. $^{165,167}\text{Yb}$ deduced levels, J, π , $B(M1)$, one-, three-quasineutron alignments. Enriched targets, Ge(Li) detectors, NaI(Tl) array, Compton-suppressed Ge(Li) coincidence set-up, mini-orange spectrometer, Si(Li) detector. NUCLEAR STRUCTURE $^{165,166,167}\text{Yb}$; calculated two-, three-quasineutron routhians, ^{166}Yb deduced two-quasineutron residual interaction. Cranked shell model.

1. Introduction

With the advent of higher-energy heavy-ion beams and improved γ -ray detection techniques it has become possible to not only extend the yrast sequence of nuclear states to higher angular momentum ^{1, 2}, but also to establish additional rotational bands quite high in angular momentum ^{3, 4}). Such detailed data for rotational bands based on several different intrinsic nuclear configurations have enticed

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theorists ^{5, 6}) to proceed with comprehensive detailed calculations of the spectrum of quasiparticle states in a rotating deformed nuclear potential. A selection of earlier references on such cranked Hartree-Fock-Bogoljubov or cranked shell-model (CSM) calculations is contained in ref. ⁷). With the initial success [see e.g. refs. ^{4-6, 8-10}] of interpreting the spectrum of energy levels in the decay scheme in terms of excitation energies of specific intrinsic configurations in a rotating frame, it seems important to establish the systematics of such quasineutron configurations as a function of neutron number.

The present article, which is a part of such a systematic study of near-yrast spectroscopy in the Yb nuclei ^{4, 8, 11, 12}), reports new level-scheme information for ^{165}Yb and ^{167}Yb and discusses near-yrast spectroscopy in $^{165-167}\text{Yb}$. The paper draws heavily on the data for the ^{166}Yb level scheme which was reported recently ^{11, 13}). A preliminary report of these data is contained in ref. ¹⁴), and some of the data were used in a recent report ¹⁵) of the systematics of band-crossing frequencies corresponding to the alignment of the first pair of $i_{1/2}$ quasineutrons.

2. Experimental techniques

The final nuclei $^{165, 167}\text{Yb}$ were produced in $^{152, 154}\text{Sm} (^{17, 18}\text{O}, \text{xn})$ reactions at beam energies of 80–84 MeV, using the $^{17, 18}\text{O}$ beams of the Niels Bohr Institute tandem accelerator. The experiments consisted of γ -ray angular distribution, $\gamma\gamma$ coincident and conversion electron coefficient measurements. Isotopically enriched ($> 98\%$) metallic targets of ^{152}Sm and ^{154}Sm mounted on ^{208}Pb backings were used for the measurements. All the measurements on ^{167}Yb were carried out with a 1.3 mg/cm^2 ^{154}Sm target on a 0.9 mg/cm^2 lead backing. A 2.5 mg/cm^2 thick ^{152}Sm target on 4.1 mg/cm^2 lead backing was used for γ -ray angular distribution and $\gamma\gamma$ coincidence measurements for ^{165}Yb , while a 1.2 mg/cm^2 ^{152}Sm target on a thinner (1.2 mg/cm^2) lead backing was used for the conversion coefficient measurement.

2.1. THE NUCLEUS ^{165}Yb

All studies of ^{165}Yb were performed in the $^{152}\text{Sm} (^{17}\text{O}, 4\text{n})$ reaction at a beam energy of 80 MeV. The relative yields of various reaction products at this bombarding energy were $\approx 60\%$ ^{165}Yb , $\approx 40\%$ ^{164}Yb and very small amounts of ^{166}Yb and ^{162}Er .

For the measurements of the angular distribution of the γ -rays, two sets of singles γ -ray spectra were obtained simultaneously at 5 different angles between 0° and 90° . A single Ge(Li) detector and a Compton-suppressed Ge(Li) detector were used for the two sets respectively. These two detectors were mounted on a common turntable at right angles to each other. A third detector placed below the target served as a monitor detector. With this set-up it was possible to deduce the angular-distribution

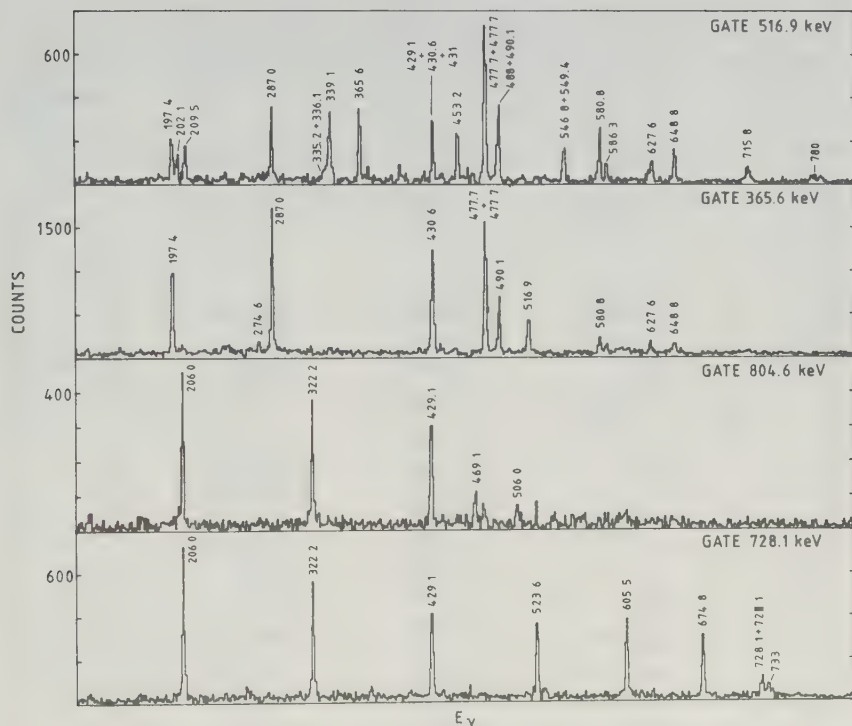


Fig. 1. Examples of γ - γ coincidence spectra from the $^{152}\text{Sm}(^{17}\text{O}, 4n)^{165}\text{Yb}$ reaction at 80 MeV, obtained with the Compton-suppressed coincidence set-up.

coefficients. For γ -ray peaks containing unresolved components of isotropic contribution from γ -rays due to radioactive nuclei, only the angular anisotropy could be determined. The efficiency calibrations at various angles were performed with a radioactive ^{152}Eu source placed at the target position. The angular-distribution coefficients were obtained by fitting the normalised peak intensities to the expression $W(\theta) = A_0 + A_2P_2(\cos \theta) + A_4P_4(\cos \theta)$. The results from the two sets of data are consistent and are summarized in table 1. The energy calibration was performed by recording a singles γ -ray spectrum at 90° along with the spectrum from a ^{152}Eu source placed near the target.

An experimental set-up consisting of five Compton-suppressed Ge(Li) detectors was used for coincidence studies. The details of the set-up will be published elsewhere¹⁶). This set-up reduces the background by about a factor of 3 for each detector, thereby making it possible both to identify weak transitions in the gated spectra and to gate on weak transitions. Furthermore, the use of five detectors renders it feasible to run a coincidence experiment with a reasonable counting rate¹⁶). In our experiment, the

TABLE I

The energies, intensities and angular distribution coefficients for the transitions assigned to ¹⁶⁵Yb following the ¹⁵²Sm(¹⁷O, 4n)¹⁶⁵Yb reaction at 80 MeV

E_γ ^{a)} (keV)	Rel. int. ^{b)}	Ang. dist. coeff. ^{c)}		Assignments	
		A_2/A_0	A_4/A_0	$I_i^\pi \rightarrow I_f^\pi$	
39.2				$\frac{9}{2}^+$	$\frac{7}{2}^-$
83.0				$\frac{11}{2}^+$	$\frac{9}{2}^+$
87.5				$\frac{7}{2}^-$	$\frac{5}{2}^-$
90.2				$\frac{13}{2}^+$	$\frac{9}{2}^+$
110.0				$\frac{9}{2}^-$	$\frac{7}{2}^-$
197.4	168	0.24(03)	-0.03(03)	$\frac{9}{2}^-$	$\frac{5}{2}^-$
202.1	147	-0.88(03)	0.14(03)	$\frac{15}{2}^+$	$\frac{13}{2}^+$
206.0	1080	0.27(01)	-0.04(01)	$\frac{17}{2}^+$	$\frac{13}{2}^+$
209.5	269	0.23(04)	-0.08(04)	$\frac{15}{2}^+$	$\frac{11}{2}^+$
274.6	14 ^{d)}			$\frac{13}{2}^-$	$\frac{11}{2}^+$
287.0	178	0.34(05)	-0.18(06)	$\frac{13}{2}^-$	$\frac{9}{2}^-$
322.2	1000	0.33(01)	-0.09(01)	$\frac{21}{2}^+$	$\frac{17}{2}^+$
335.2	75	-0.81(06)	0.23(07)	$\frac{19}{2}^+$	$\frac{17}{2}^+$
336.1	weak			$\frac{33}{2}^-$	$\frac{31}{2}^+$
339.1	310	0.31(02)	-0.07(02)	$\frac{19}{2}^+$	$\frac{15}{2}^+$
365.6	177	0.35(02)	-0.12(03)	$\frac{17}{2}^-$	$\frac{13}{2}^-$
429.1	851	0.34(02)	-0.08(02)	$\frac{25}{2}^+$	$\frac{21}{2}^+$
430.6	190 ^{d)}	0.33(03)	-0.11(03)	$\frac{21}{2}^-$	$\frac{17}{2}^-$
431	weak			$\frac{17}{2}^-$	$\frac{15}{2}^+$
453.2	338	0.35(03)	-0.11(03)	$\frac{23}{2}^+$	$\frac{19}{2}^+$
466.1	80	-0.38(10)	0.12(10)	$\frac{23}{2}^+$	$\frac{21}{2}^+$
469.1	38	0.22(10)	0.13(10)	$\frac{31}{2}^-$	$\frac{27}{2}^-$
477.7 } 477.7 }	341	0.33(07)	-0.07(07)	$\frac{25}{2}^-$	$\frac{21}{2}^-$
488	85 ^{d)}			$\frac{33}{2}^-$	$\frac{29}{2}^-$
490.1	110 ^{d)}	0.29(02)	-0.08(02)	$\frac{29}{2}^-$	$\frac{27}{2}^+$
506.0	121	0.24(06)	-0.13(06)	$\frac{35}{2}^-$	$\frac{31}{2}^-$
516.9	116	0.41(05)	-0.05(05)	$\frac{37}{2}^-$	$\frac{33}{2}^-$
522	30 ^{d)}			$\frac{21}{2}^-$	$\frac{19}{2}^+$
523.6	644	0.31(05)	-0.06(05)	$\frac{29}{2}^+$	$\frac{25}{2}^+$
541.5	19	-0.46(36)	-0.13(40)	$\frac{39}{2}^-$	$\frac{37}{2}^+$
546.8	42	-0.39(14)	-0.10(14)	$\frac{25}{2}^-$	$\frac{23}{2}^+$
549.4	219	0.32(05)	-0.06(05)	$\frac{27}{2}^+$	$\frac{23}{2}^+$
566.0	84	0.34(06)	-0.12(06)	$\frac{39}{2}^-$	$\frac{35}{2}^-$
580.8	106	0.32(04)	0.01(04)	$\frac{41}{2}^-$	$\frac{37}{2}^-$
586.3	54	-0.12(12)	0.00(13)	$\frac{27}{2}^+$	$\frac{23}{2}^+$
605.5	398	0.28(03)	-0.05(03)	$\frac{33}{2}^+$	$\frac{29}{2}^+$
627.6	74	0.38(10)	0.10(12)	unassigned	
629.1	141	0.19(06)	0.02(06)	$\frac{31}{2}^+$	$\frac{27}{2}^+$
635.4	39	0.21(10)	0.00(10)	$\frac{43}{2}^-$	$\frac{39}{2}^-$
648.8	48	0.40(14)	0.00(14)	$\frac{45}{2}^-$	$\frac{41}{2}^-$

TABLE 1 (continued)

E_γ ^{a)} (keV)	Rel. int. ^{b)}	Ang. dist. coeff. ^{c)}		Assignments	
		A_2/A_0	A_4/A_0	$I_i^\pi \rightarrow I_f^\pi$	
650.4	75	-0.23(05)	-0.05(06)	$\frac{3.5}{2}-$	$\frac{3.3}{2}+$
674.8	199	0.25(04)	-0.07(04)	$\frac{3.7}{2}+$	$\frac{3.3}{2}+$
695.1	53	0.14(10)	0.07(10)	$\frac{3.5}{2}+$	$\frac{3.1}{2}+$
704	26				$\frac{2.3}{2}+$
706.0	36	0.24(10)	-0.02(10)	$\frac{4.7}{2}-$	$\frac{4.3}{2}-$
715.8	20	0.44(28)	0.01(28)	$\frac{4.9}{2}-$	$\frac{4.5}{2}-$
728.1 } 728.1 }	108	0.15(06)	-0.11(06)	$\frac{4.1}{2}+$	$\frac{3.7}{2}+$
				$\frac{4.5}{2}+$	$\frac{4.1}{2}+$
733	14 ^{d)}			($\frac{4.9}{2}+$)	$\frac{4.5}{2}+$
749.1	36	0.38(29)	-0.51(29)	$\frac{3.2}{2}+$	$\frac{3.5}{2}+$
750.1	63	-0.42(19)	0.43(22)	$\frac{3.1}{2}-$	$\frac{2.9}{2}+$
771	weak				$\frac{2.1}{2}+$
775	weak			$\frac{4.1}{2}-$	$\frac{4.7}{2}-$
780	22	0.74(30)	-0.34(20)	$\frac{5.3}{2}-$	$\frac{4.9}{2}-$
804.6	51	-0.47(13)	0.32(14)	$\frac{2.7}{2}-$	$\frac{2.5}{2}+$

^{a)} The energies are accurate to within 0.2 keV for strong lines (rel. int. ≥ 100). For weaker lines, the error may rise to 0.5 keV.

^{b)} Estimated errors are less than 10 % for strong lines. For weak lines errors may rise to 20 %.

^{c)} Only fitting errors are given.

^{d)} From coincidence data, not corrected for possible angular correlation effects.

gains of the amplifiers of the Ge(Li) detectors were matched. In all, about 22 million Compton-suppressed coincidence events were accumulated on tapes for off-line analysis. The tapes were sorted for all possible combinations of detectors, and the resultant spectra, after background subtraction, were added together. Examples of coincidence spectra are shown in fig. 1.

A 1-fold conversion electron spectrum gated by a multiplicity filter was acquired at 55° with a mini-orange spectrometer with a cooled Si(Li) detector. A 1-fold γ -ray spectrum gated by the same multiplicity filter was acquired simultaneously at -125°. The conversion coefficients were normalised to the $\alpha_K(E2)$ values of the 605.5 and 674.8 keV transitions in ^{165}Yb .

2.2. THE NUCLEUS ^{167}Yb

The coincidence run for ^{167}Yb was made with a 80 MeV ^{17}O beam on a ^{154}Sm target, using three large-volume Ge(Li) detectors and one planar Ge(Li) detector, together with four large-volume NaI(Tl) detectors serving as a multiplicity filter. The gains of the three large-volume Ge(Li) detectors were matched. About 200 million two- or higher-fold coincidence events, in which at least two of the detectors

TABLE 2

The energies, intensities and angular distribution coefficients for the transitions assigned to ^{167}Yb following the $^{154}\text{Sm}(^{18}\text{O}, 5n)^{167}\text{Yb}$ reaction at 84 MeV

E_γ ^{a)} (keV)	Rel. int. ^{b)}	Ang. dist. coeff. ^{c)}		Assignments	
		A_2/A_0	A_4/A_0	$I_1^\pi \rightarrow I_f^\pi$	
29.6 ^{d)}				$\frac{3}{2}^+$	$\frac{3}{2}^-$
33.8 ^{d)}				$\frac{7}{2}^+$	$\frac{7}{2}^-$
60.1	360 ^{e)}			$\frac{13}{2}^+$	$\frac{11}{2}^+$
61.1				$\frac{23}{2}^+$	$\frac{23}{2}^+$
67.4				$\frac{11}{2}^+$	$\frac{9}{2}^+$
76.9				$\frac{21}{2}^+$	$\frac{19}{2}^+$
77.7	150 ^{f)}			$\frac{17}{2}^+$	$\frac{13}{2}^+$
78.6				$\frac{7}{2}^-$	$\frac{5}{2}^-$
91.9				$\frac{11}{2}^+$	$\frac{7}{2}^+$
100.1				$\frac{9}{2}^-$	$\frac{7}{2}^-$
120.2	55	0.04(17)	-0.09(19)	$\frac{9}{2}^-$	$\frac{9}{2}^+$
127.5	413	0.25(03)	-0.06(03)	$\frac{13}{2}^+$	$\frac{9}{2}^+$
144.2	458	-0.78(03)	0.14(07)	$\frac{13}{2}^+$	$\frac{13}{2}^+$
144.9	80 ^{f)}			$\frac{9}{2}^-$	$\frac{7}{2}^+$
178.7	78	0.09(06)	-0.01(07)	$\frac{9}{2}^-$	$\frac{5}{2}^-$
204.4	760	0.27(03)	-0.05(04)	$\frac{15}{2}^+$	$\frac{11}{2}^+$
221.9	1000	0.28(03)	-0.06(04)	$\frac{17}{2}^+$	$\frac{13}{2}^+$
236.5	286	-0.72(03)	-0.01(03)	$\frac{19}{2}^+$	$\frac{17}{2}^+$
263.5	152	0.21(02)	-0.03(02)	$\frac{13}{2}^-$	$\frac{9}{2}^-$
313.5	1760	0.47(16)	-0.18(16)	$\frac{21}{2}^+$	$\frac{17}{2}^+$
314.2	533	0.23(11)	-0.13(12)	$\frac{19}{2}^+$	$\frac{15}{2}^+$
316.6	147 ^{g)}	0.41(05)	0.10(05)	$\frac{13}{2}^-$	$\frac{11}{2}^+$
339.4	130	-0.65(03)	-0.08(04)	$\frac{23}{2}^+$	$\frac{21}{2}^+$
341.2	232	0.26(02)	-0.09(02)	$\frac{17}{2}^-$	$\frac{13}{2}^-$
400.5	1515	0.28(04)	-0.07(05)	$\frac{25}{2}^+$	$\frac{21}{2}^+$
409.1	330	0.33(03)	-0.06(03)	$\frac{21}{2}^-$	$\frac{17}{2}^-$
416.4	616	0.24(03)	-0.04(03)	$\frac{23}{2}^+$	$\frac{19}{2}^+$
447.8	73	-0.52(05)	0.13(06)	$\frac{27}{2}^+$	$\frac{25}{2}^+$
453	120 ^{f)}			$\frac{17}{2}^-$	$\frac{15}{2}^+$
463.9	343	0.25(03)	-0.03(04)	$\frac{25}{2}^-$	$\frac{21}{2}^-$
479.4	1275	0.26(04)	-0.06(04)	$\frac{29}{2}^+$	$\frac{25}{2}^+$
501.8	331	0.22(02)	-0.10(03)	$\frac{29}{2}^-$	$\frac{25}{2}^-$
508.9	660	0.20(03)	-0.05(04)	$\frac{27}{2}^+$	$\frac{23}{2}^+$
525	weak			$\frac{33}{2}^-$	$\frac{31}{2}^+$
525.3	344	0.18(03)	-0.07(03)	$\frac{33}{2}^-$	$\frac{29}{2}^-$
547.0	1030	0.26(05)	-0.08(05)	$\frac{33}{2}^+$	$\frac{29}{2}^+$
548	40 ^{f)}			$\frac{21}{2}^-$	$\frac{19}{2}^+$
553	524 ^{g)}	0.48(07)	-0.19(07)	$\frac{37}{2}^-$	$\frac{33}{2}^-$
557.4	weak			$\frac{31}{2}^+$	$\frac{29}{2}^+$
588.9	425 ^{g)}	0.17(02)	-0.02(02)	$\frac{31}{2}^+$	$\frac{27}{2}^+$
589	weak			$\frac{29}{2}^-$	$\frac{27}{2}^+$

TABLE 2 (continued)

E_γ ^{a)} (keV)	Rel. int. ^{b)}	Ang. dist. coeff. ^{c)}		Assignments	
		A_2/A_0	A_4/A_0	$I_1^\pi \rightarrow I_2^\pi$	
596	weak			$\frac{2.5}{2}-$	$\frac{2.3}{2}+$
600	227	0.22(06)	-0.07(07)	$\frac{4.1}{2}-$	$\frac{3.7}{2}-$
602.8	775 ^{e)}	0.19(02)	-0.05(03)	$\frac{3.7}{2}+$	$\frac{3.3}{2}+$
647.6	340 ^{e)}	0.08(02)	0.06(03)	$\frac{4.1}{2}+$	$\frac{3.7}{2}+$
658	240	0.13(04)	0.06(05)	$\frac{3.5}{2}+$	$\frac{3.1}{2}+$
660	weak			$\frac{4.5}{2}-$	$\frac{4.1}{2}-$
692.3	bad background			$\frac{4.5}{2}+$	$\frac{4.1}{2}+$
715	weak			$\frac{3.9}{2}+$	$\frac{3.5}{2}+$
716	weak			$\frac{4.9}{2}-$	$\frac{4.5}{2}-$
742	weak			$\frac{4.9}{2}+$	$\frac{4.5}{2}+$
760	weak			$\frac{4.3}{2}+$	$\frac{3.9}{2}+$
801	weak			$\frac{5.3}{2}+$	$\frac{4.9}{2}+$

^{a)} Estimated errors are less than 0.2 keV for the strong lines (rel. int. ≥ 200), rising to 0.5 for weaker lines.

^{b)} Estimated errors are less than 10 % for strong lines. For weak lines it may rise to 20 %.

^{c)} Only fitting errors are given.

^{d)} From ref. ¹⁹⁾.

^{e)} From intensity balance of the transitions feeding and depopulating the $\frac{1}{2}^+$ level.

^{f)} From coincidence data, not corrected for possible angular correlation effects.

^{g)} Not corrected for the contribution from contaminant lines.

triggered were Ge(Li) detectors, were accumulated on magnetic tapes for off-line analysis. Examples of coincidence spectra are shown in fig. 2. The reaction at this bombarding energy resulted in almost equal amounts of ^{166}Yb and ^{167}Yb . The data for ^{166}Yb extracted from this experiment were a valuable aid in the interpretation of the coincidence data obtained in a previous run ¹¹⁾ for ^{166}Yb . This was mainly due to the complete absence of the contaminant lines from ^{165}Yb in this experiment in contrast to the previous experimental study of ^{166}Yb .

The $^{154}\text{Sm}(^{18}\text{O}, 5n)^{167}\text{Yb}$ reaction at a beam energy of 84 MeV was used for the angular distribution coefficient measurement. Singles γ -ray spectra were obtained at 9 different angles between -90° and 90° , the reaction being monitored by a detector at 155° . The efficiency calibrations at various angles were performed with ^{152}Eu and ^{177}Lu sources placed at the target position. Energies of the γ -rays were determined by recording simultaneously at 90° the γ -rays from the reaction and γ -rays from ^{152}Eu and ^{137}Cs sources. The results of these measurements are summarised in table 2.

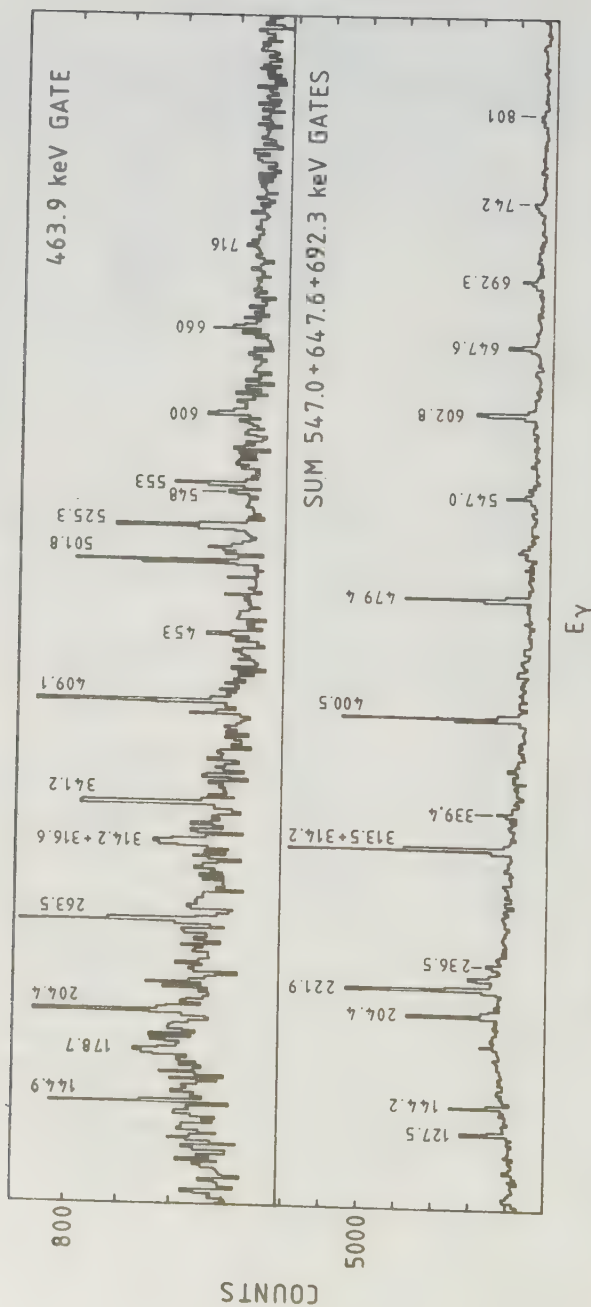


Fig. 2. Examples of γ - γ coincidence spectra from the $^{154}\text{Sm}(^{17}\text{O}, 4n)^{167}\text{Yb}$ reaction at 80 MeV.

3. Construction of the level schemes

3.1. THE NUCLEUS ^{165}Yb

High-spin states in ^{165}Yb have previously been studied by Riedinger *et al.* ¹⁷⁾ and Richter *et al.* ¹⁸⁾. The level scheme of ^{165}Yb , as deduced from the present studies, is presented in fig. 3. The spin and parity assignments are based on the angular-distribution and conversion-coefficient measurements (cf. table 1). All the transitions within a band are found to be of stretched E2 type.

Based on the systematics of Nilsson orbitals in this region, the ground state of ^{165}Yb has been classified as $[523]_{\frac{5}{2}}^{-}$ (see subsect. 4.2). The ground-state band has been observed up to a spin of $\frac{53}{2}^{-}$ in the present study. The ordering of the transitions is based on the coincidence relationships and the identification of six interband transitions connecting this band to the unfavoured member of the band based on the $i_{\frac{13}{2}}$ neutron orbital. This order differs from those given in refs. ^{17, 18)}, which were obtained from the singles γ -ray intensities and from coincidence relationships in spectra obtained by gating on low-lying transitions. In the present study, on the other hand, it has been possible to gate on high-lying transitions (cf. fig. 1). A 627.6 keV transition, which probably feeds the level at 4472.7 keV, is weak and its multipolarity could not be deduced from the present studies.

The favoured sequence of states based on the $i_{\frac{13}{2}}$ shell model orbital forms the yrast states and is most strongly populated. Although the 39 keV $\frac{3}{2}^{+} \rightarrow \frac{1}{2}^{+}$ transition, which was reported in refs. ^{17, 18)}, has not been observed in the present study, the relative positions of the levels, as deduced from the identification of interband transitions connecting the high-spin states, lend support to its existence. On the basis of the results of $e^{-}\gamma$ coincidence experiment, Richter *et al.* ¹⁸⁾ assigned the 804.6 keV γ -ray as a $\frac{45}{2}^{+} \rightarrow \frac{41}{2}^{+}$ transition. However, the present data shows that this transition feeds the $\frac{25}{2}^{+}$ level. The 728.1 keV peak is a self-coincident doublet. A weak line at 733 keV is found to be in coincidence with all the members of the cascade 206, 322, . . . , 728 and its intensity relative to the low-lying members of the cascade increases as one gates higher up in the cascade. Moreover, the intensity of this line in the spectrum gated by the 728.1 keV line is almost twice as much as that in the spectrum gated by the 675 keV line. Based on these facts, we arrived at the sequence 728.1, 728.1, 733. Based on the measured angular distribution coefficients and the conversion coefficient $\alpha_K = 7(2) \times 10^{-3}$, both the 728.1 keV transitions are assigned to be of the stretched E2 type. The 733 keV transition is tentatively assigned as the $(\frac{49}{2}^{+}) \rightarrow \frac{45}{2}^{+}$ transition. The unfavoured members of the positive-parity band have been observed up to spin $\frac{39}{2}^{+}$. The 704 keV γ -ray assigned by Richter *et al.* ¹⁸⁾ as the $\frac{35}{2}^{+} \rightarrow \frac{31}{2}^{+}$ transition is found to feed the $\frac{23}{2}^{+}$ level.

A negative-parity band based on the level at 1979.2 keV has been assigned to ^{165}Yb . This band is joined by means of four interband transitions to the positive-parity band. Although the 804.6 keV transition is the strongest γ -line depopulating this band, the measured angular distribution coefficients of this line entail considerable uncer-

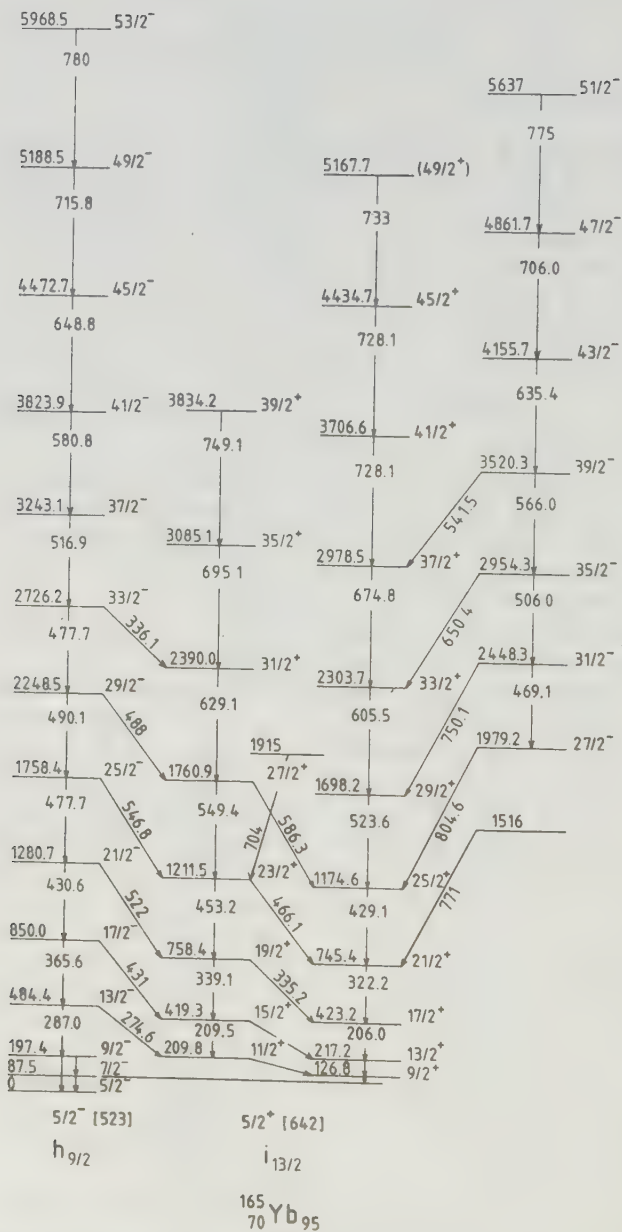


Fig. 3. Level scheme of ^{165}Yb , showing states populated in the $^{152}\text{Sm}(^{17}\text{O}, 4n)^{165}\text{Yb}$ reaction at 80 MeV.

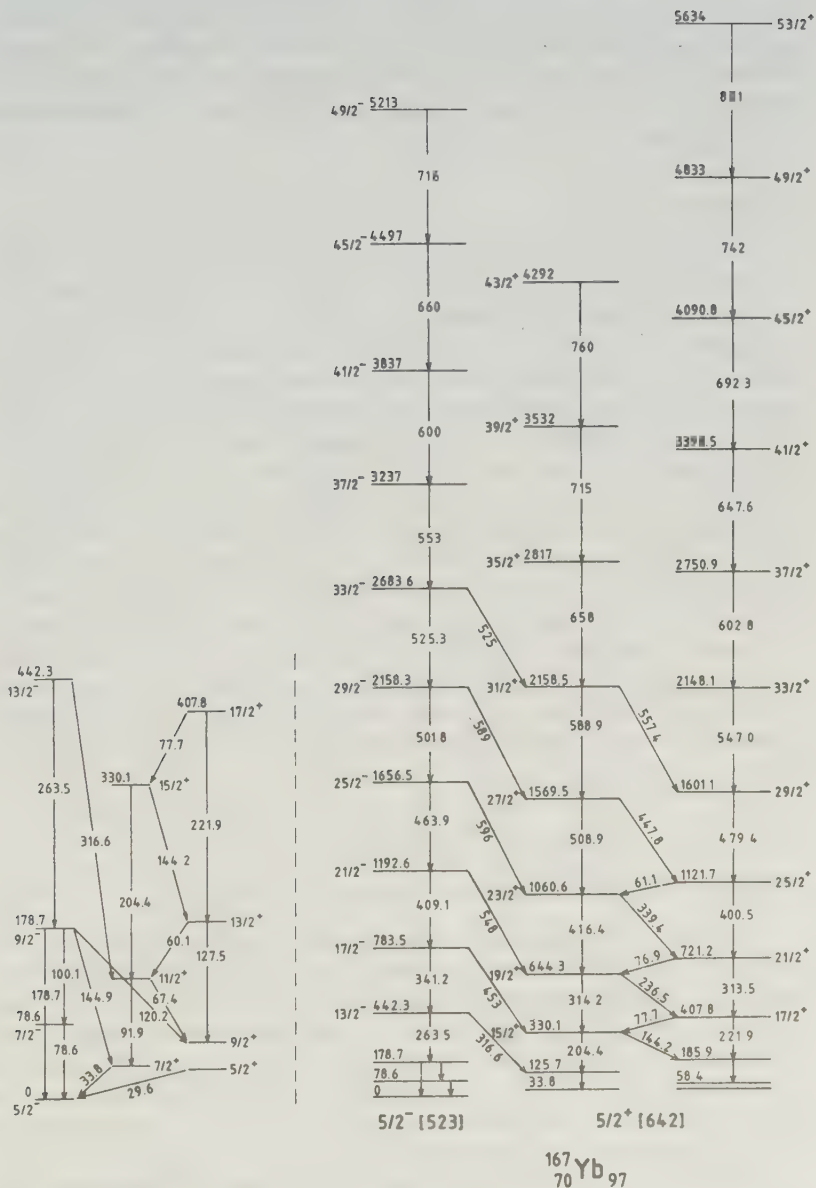


Fig. 4. Level scheme of ^{167}Yb , showing states populated in the $^{154}\text{Sm}(^{17}\text{O}, 4n)^{167}\text{Yb}$ reaction at 80 MeV.

tainties due to the presence of the Doppler broadened 803 keV line originating from Coulomb excitation of ^{206}Pb found in the beam-stop. Nevertheless, the measured angular distribution coefficients of all the interband transitions, combined with the conversion coefficient $\alpha_K < 4 \times 10^{-3}$, of the 804.6 keV line establish the spin sequence and parity of this band. The level at 1516 keV may be a low-spin continuation of this band.

3.2. THE NUCLEUS ^{167}Yb

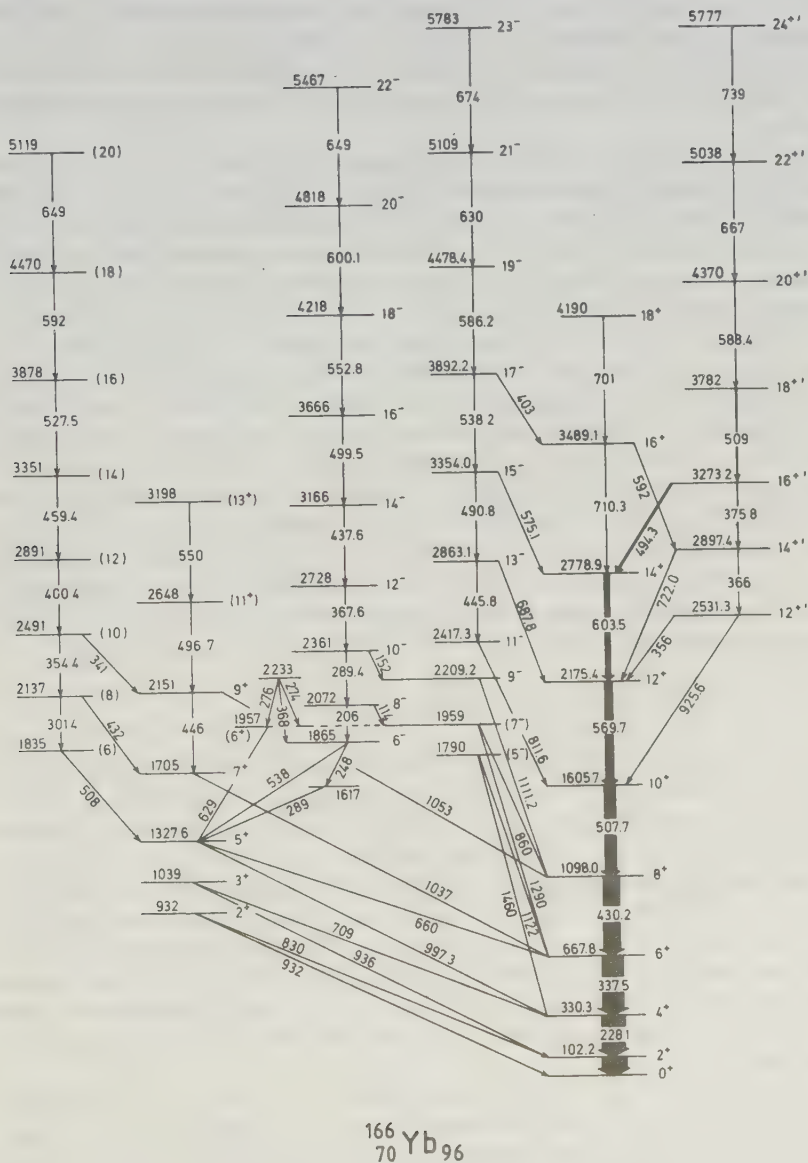
Lindblad¹⁹ studied the nucleus ^{167}Yb using the $(\alpha, 3n)$ reaction. The level scheme for ^{167}Yb , as constructed from the present studies, is presented in fig. 4. The low-spin part of the level scheme is in agreement with that of ref. ¹⁹). The ground state of ^{167}Yb is classified as $[523]\frac{5}{2}^-$ from the systematics of the Nilsson levels in this region (see subsect. 4.2). The ground-state band has been extended up to a spin $\frac{49}{2}^-$ from a known $\frac{25}{2}^-$ state. The favoured and the unfavoured members of the band based on the $[642]\frac{5}{2}^+$ quasiparticle state have been extended up to spins $\frac{53}{2}^+$ and $\frac{43}{2}^+$, respectively, from $\frac{33}{2}^+$ and $\frac{31}{2}^+$ known from ref. ¹⁹). We have furthermore identified several interband transitions depopulating members of the negative-parity band. The low energy M1/E2 transitions between the two different signatures of the positive-parity band are based on the coincidence data. The nucleus ^{167}Yb has recently been studied in Brookhaven²⁰) using a Be beam and a similar level scheme has been established. Although some of the transitions belonging to a band based on $[505]\frac{11}{2}^-$ as proposed by Lindblad¹⁹), are seen in the present work, no conclusions could be drawn about this band due to the weakness of these transitions. It is to be noted that the levels of the $[505]\frac{11}{2}^-$ band are expected to lie high above the yrast levels of similar spins, and, consequently, this band would be faintly populated in heavy-ion reactions, if populated at all.

4. Discussion

4.1. TRANSFORMATION TO e' VERSUS $\hbar\omega$ REPRESENTATION

It is generally accepted that the decay sequences established for medium- and heavy-mass rare-earth nuclei are composed of cascades along a series of rotational bands each based on a particular configuration. In order to study the effect of rotation on independent-particle motion in a deformed nucleus, it is convenient to transform the spectrum of energy levels contained in the decay scheme (e.g. see figs. 3–5) to excitation energies in a rotating “intrinsic” frame (routhians, e') as a function of the angular frequency ($\hbar\omega \approx \frac{1}{2}E_\gamma$ for $\Delta I = 2$). In the e' versus $\hbar\omega$ representation it is possible to obtain information on the energy contribution to the nucleus in the intrinsic frame, from the rotational motion, since the hamiltonian h^ω for independent-particle motion in a rotating deformed nucleus is:

$$h^\omega = h^0 - \omega j_1, \quad (1)$$



$\hbar^0$ is here the quasiparticle hamiltonian in a static, deformed field (e.g. the field of the Nilsson model) and ωj_1 is the Coriolis and centrifugal term with j_1 being the projection of the single-particle angular momentum on the axis of rotation (the 1-axis), taken to be perpendicular to the symmetry axis. Such information is available for the nuclear configuration corresponding to each rotational sequence in the decay scheme.

The detailed prescription for the transformation to excitation in a rotating frame and to $\hbar\omega$ is given in the literature [see e.g. ref. ⁶⁾] and, therefore, will not be given explicitly in this paper. The procedure is to subtract the rotational energy, i.e. ωI_1 (I_1 is the component of the total angular momentum along the axis of rotation), from the excitation energy. In order to compare the intrinsic-frame excitation energies between different nuclei and also with the results of calculations, it is convenient to establish a reference frame. Two choices of reference frame are in common use: the even-even nucleus ground-state configuration ⁶⁾ and the yrast configuration ²¹⁾ of the even-even nucleus (see fig. 6). For odd- N or odd- Z nuclei the routhians are referred to the appropriate reference configuration of the neighbouring even-even nucleus and the pairing-correlation parameter Δ is added ⁶⁾. However, technical problems are associated with both choices of reference frames. The ground-state band moment of inertia is not constant at the lowest $\hbar\omega$ and this band is not known at higher $\hbar\omega$. Therefore, for the ground-state reference it is necessary to choose an appropriate parameterized reference as a function of $\hbar\omega$ to approximate the zero-quasiparticle ground-state configuration. The choice can then be a band with a variable moment of inertia ²²⁾, as described by the Harris formula ²³⁾

$$\mathcal{J} = \mathcal{J}_0 + \omega^2 \mathcal{J}_1, \quad (2)$$

with $\mathcal{J}_1 = 90 \text{ MeV}^{-3} \cdot \hbar^4$ and $\mathcal{J}_0 = 27.8, 29.8$ and $31.8 \text{ MeV}^{-1} \cdot \hbar^2$, respectively for ¹⁶⁵Yb, ¹⁶⁶Yb and ¹⁶⁷Yb. These parameters, which are similar to those used for lighter Yb isotopes ^{4, 24)}, are a compromise between the values necessary to produce constant alignment in the ground-state band ($\mathcal{J}_1 \approx 125 \text{ MeV}^{-3} \cdot \hbar^4$ in ¹⁶⁶Yb) and in the yrast sequence above the lowest-frequency band crossing, the S-band ²⁵⁾ ($\mathcal{J}_1 \approx 70 \text{ MeV}^{-3} \cdot \hbar^4$). The use of such an average reference frame results in a slight increase in the alignment i with increasing frequency in the ground-state band and a small decrease of i with $\hbar\omega$ in the S-band. The smooth variation of the Harris parameters with neutron number ($\mathcal{J}_1$ constant and $\mathcal{J}_0$ only slightly N -dependent) makes it possible to discuss the rotational effects on quasineutron states in neighbouring isotopes.

Problems associated with the extrapolation of the ground-state reference frame to higher $\hbar\omega$ can be circumvented by referring the intrinsic-frame excitation energies to the yrast band. The yrast configuration of even-even nuclei, however, is not necessarily appropriate for the neighbouring odd-mass isotopes and isotones. For example, a difference in pairing and interaction strengths between odd- and even- N

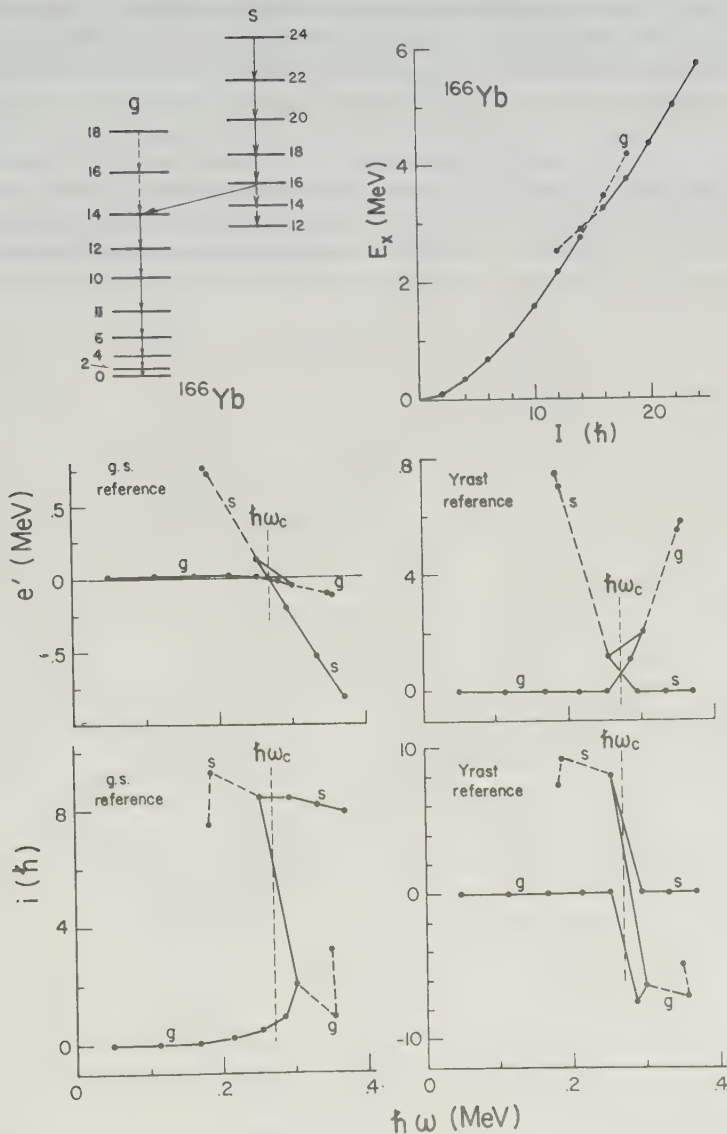


Fig. 6. Routhians and alignments as a function of $\hbar\omega$ for the ground-state band and the S-band in ^{166}Yb , referred to the g.s.b. reference (shown to the left), and to the yrast reference (shown to the right). A partial decay scheme of ^{166}Yb and an E_x versus I plot showing the levels of the g.s.b. and the S-band are also shown in the upper portion of the figure.

(or Z) neighbours will produce changes in the reference appropriate for odd- and even- N (or Z) systems. Such problems will be discussed in subsect. 4.4 where experimentally constructed routhians are compared directly with calculated values.

Information about the alignment, i , also is contained in the e' versus $\hbar\omega$ plots with

$$i \equiv \sum j_1 = -\frac{de'}{d\omega}. \quad (3)$$

(From eq. (1) and $e' \equiv \langle h^\omega \rangle$.) It is often convenient to plot i versus $\hbar\omega$, perhaps because of the similarity of such a presentation of the data with the familiar "back-bending" plot. The alignments are also shown in fig. 6 as a function of $\hbar\omega$ for the yrast

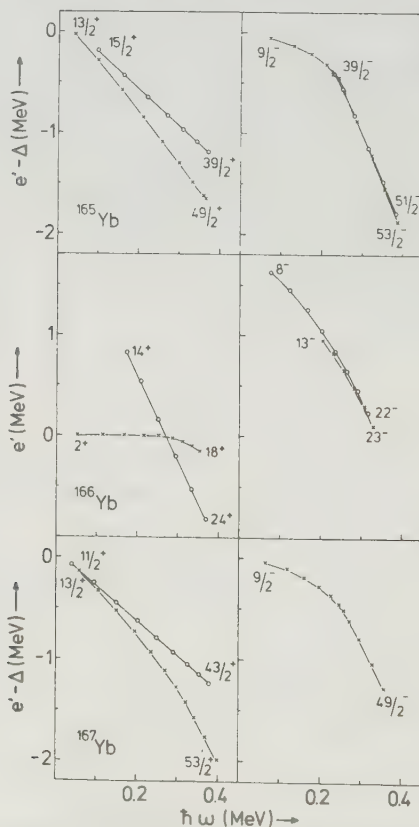


Fig. 7a. Experimental routhians for various bands in 165 , 166 , ^{167}Yb , referred to the ground-state bands and their smooth extrapolations. The Harris parameters used for the reference configurations are $\mathcal{H}_1 = 90 \text{ MeV}^{-3} \cdot \hbar^4$ and $\mathcal{H}_0 = 27.8, 29.8, 31.8 \text{ MeV}^{-1} \cdot \hbar^2$, respectively for ^{165}Yb , ^{166}Yb and ^{167}Yb . For ^{166}Yb a ground-state band S-band interaction of 50 keV [see ref. ¹¹]] has been assumed.

sequence of ^{166}Yb referred to both the ground-state band and the yrast references. Near $\hbar\omega_c$, the angular frequency of the band crossing, the excitation energy of the yrast sequence is double-valued for a particular $\hbar\omega$ ("backbending"). It is, therefore, necessary to define which branch of the yrast sequence that is to be taken as the reference: for $\hbar\omega < \hbar\omega_c$ the ground-state band is used as reference; for $\hbar\omega > \hbar\omega_c$ the S-band is taken as reference. ($\hbar\omega_c$ is defined as the angular frequency where the ground-state band and S-band routhians cross.) The appearance of a crossing between the weakly-interacting bands in e' and i plots referred both to the ground-state and the yrast configurations are shown in fig. 6.

Since the present work is confined to reasonably low values of $\hbar\omega$, where the

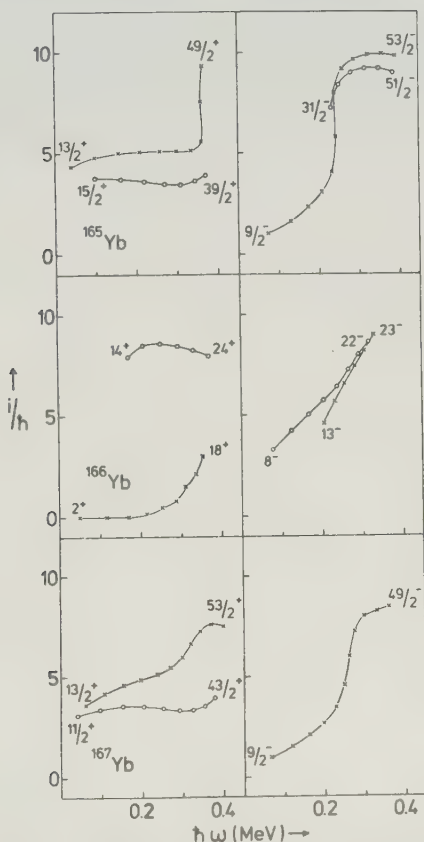


Fig. 7b. Experimental alignments for various bands in $^{165,166,167}\text{Yb}$, referred to the ground-state bands. For the values of the Harris parameters and the interaction assumed in ^{166}Yb , see the caption for fig. 7a.

extrapolation of the ground-state configuration is reasonable, the data will usually be referred to a parameterized ground-state configuration [eq. (2)]. For example, the level scheme information for $^{165, 166, 167}\text{Yb}$ is shown transformed to the rotating frame and referred to the ground-state configuration in fig. 7. In ^{167}Yb , however, where there are strong interactions between the quasiparticle configurations, it is more convenient to choose a yrast reference (see subsect. 4.4).

4.2. THE SPECTRUM OF SINGLE-QUASINEUTRON STATES IN $^{165, 167}\text{Yb}$

Three bands are known, in both ^{165}Yb and ^{167}Yb , which can be interpreted as

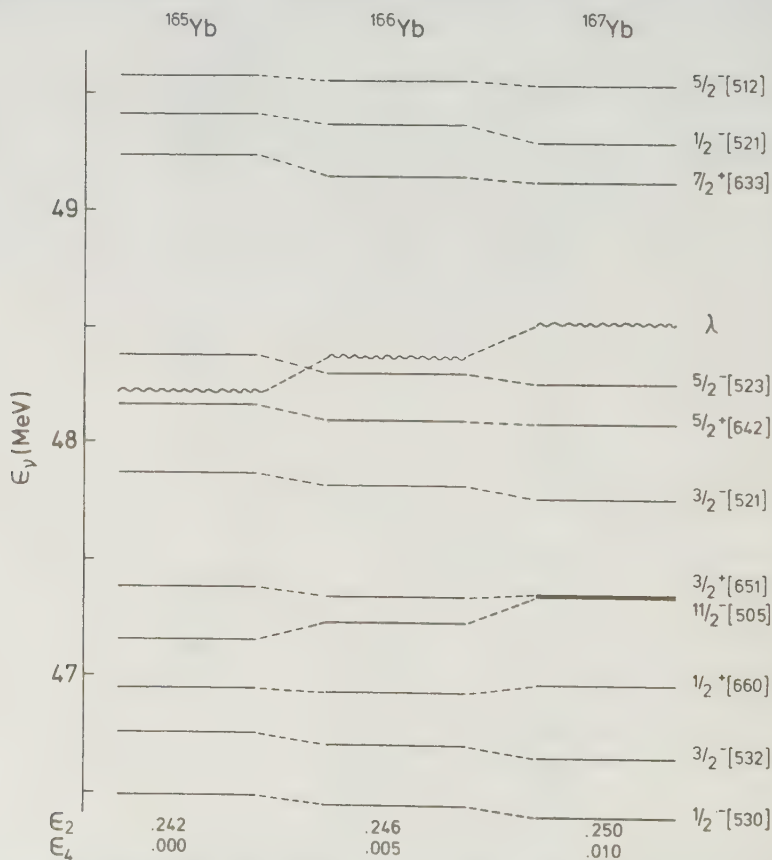


Fig. 8. Nilsson states near the Fermi surface for $^{165, 166, 167}\text{Yb}$. The deformation parameters assumed, shown at the bottom and the Nilsson parameters used are from refs. ^{9, 28}). The position of the Fermi surface is labelled by λ .

rotational bands based on single-quasineutron intrinsic configurations: the ground-state band with $(\pi, \alpha)_n = (-, +)_1$ and the favoured and unfavoured portions of the yrast band with $(\pi, \alpha)_n = (+, +)_1$ and $(+, -)_1$ respectively. The systematics of the single-quasiparticle state routhians are as expected from the Nilsson states near the Fermi surface (see fig. 8). The $K^\pi = \frac{5}{2}^-$ ground-state band in both odd- N nuclei is expected to correspond to the $\frac{5}{2}^-$ [523] Nilsson orbit at $\hbar\omega = 0$, which is expected to lie just above the Fermi surface in ^{165}Yb and just below the Fermi surface in ^{167}Yb . This Nilsson orbit is based on a dominantly $h_{7/2}$ shell-model state; therefore, because of the relatively large Ω when compared to j , this configuration is expected to obtain only a small alignment when rotated. In contrast, the yrast bands are expected and observed to have larger rotational alignments. These bands in both ^{165}Yb and ^{167}Yb are based on the $(+, +)_1$ and $(+, -)_1$ intrinsic configurations that at $\hbar\omega = 0$ correspond to the $\frac{5}{2}^+$ [642] Nilsson configuration which involves the larger j of the $i_{13/2}$ neutrons. Furthermore, the highly alignable $\frac{3}{2}^+$ [651] and $\frac{1}{2}^+$ [660] Nilsson configurations are sufficiently close to the Fermi surface (see fig. 8) to mix into the yrast configurations at higher $\hbar\omega$. Indeed the sizable energy splitting between the routhians corresponding to the different signatures of the yrast configuration, i.e. $(+, +)_1$ and $(+, -)_1$, is a measure of the $\Omega = \frac{1}{2}$ component in the wave function. The decrease in the observed signature splitting between ^{165}Yb and ^{167}Yb (see fig. 7), therefore, is a result of the shift of the Fermi surface away from the low- Ω orbits with increasing neutron number. Such a decrease in signature splitting is systematically observed²⁴⁾ with increasing neutron number between ^{161}Yb and ^{167}Yb .

4.3. CONSTRUCTION OF MULTIPLE-QUASINEUTRON STATES FROM THE SPECTRUM OF SINGLE-QUASINEUTRON STATES

The single-quasineutron states such as the three observed experimentally in $^{165}, ^{167}\text{Yb}$, represent the building blocks for the construction of multiple-quasineutron states. From the energies of these states in the intrinsic system, e's, it is possible to construct experimental estimates of excitation energies as a function of $\hbar\omega$ for multiple-quasiparticle states. For example, the e's corresponding to the lowest expected two-quasiparticle, positive-parity configuration, $(+, 0)_1^2$, and the two lowest two-quasiparticle, negative-parity configurations $(-, 1)_1^2$ and $(-, 0)_1^2$ in ^{166}Yb can be constructed from the known single-quasineutron configurations $((+, +)_1, (+, -)_1$ and $(-, +)_1$) in $^{165}, ^{167}\text{Yb}$ (see fig. 9), $(+, 0)_1^2 = [(+, +)_1 \times (+, -)_1]_1^2$, $(-, 1)_1^2 = [((+, +)_1 \times (-, +)_1)]_1^2$ and $(-, 0)_1^2 = [((+, -)_1 \times (-, +)_1)]_1^2$. Two of the constructed two-quasineutron configurations, $(+, 0)_1^2$, i.e. the S-band, and

[†] The rotational configurations are labelled by the conserved quantum numbers of the corresponding intrinsic quasiparticle configurations, parity, π , and signature, α ($+$ or $-$ corresponds to $\alpha = +\frac{1}{2}$ or $-\frac{1}{2}$; when $\alpha = 1$ or 0 it is explicitly stated). The n designates that this configuration is the n th such configuration with these quantum numbers. A superscript, S is added, $(\pi, \alpha)_n^S$, to multi-quasiparticle states to designate the seniority of the configuration. Note that the π of a multiple-quasiparticle configuration is the product of those of the constituent quasiparticles, whereas the α of the multiple-quasiparticle configuration is the sum of the α 's of the constituent quasiparticles.

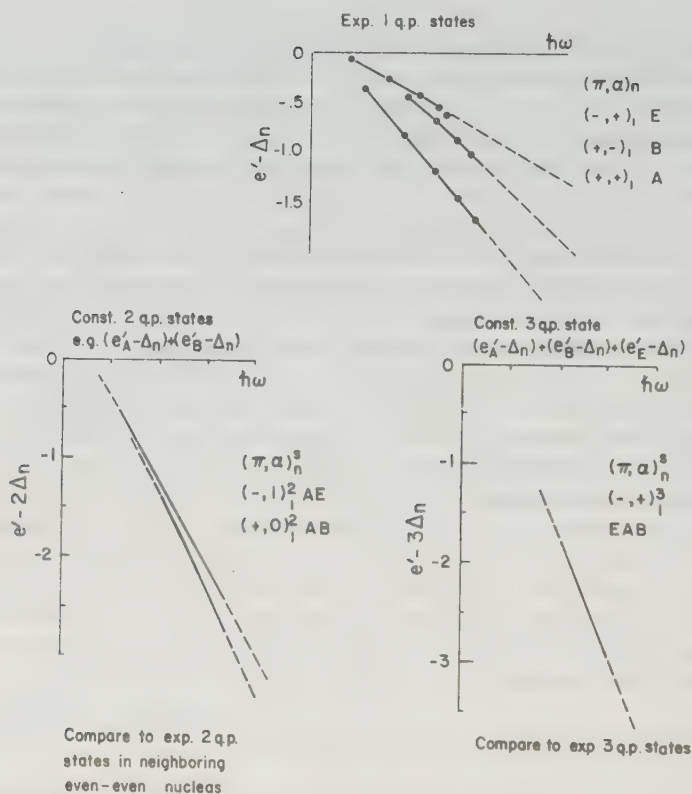


Fig. 9. Schematic figure illustrating construction of 2- and 3-q.p. routhians using 1-q.p. routhians. Note that the neutron pairing correlation parameter, Δ_n , has not been added to the routhians. The dashed lines represent routhians for those ranges of $\hbar\omega$, for which routhians for one or more constituent quasiparticles have been extrapolated.

$(-, 1)_1^2$, the lowest negative-parity band, are known in ^{166}Yb . Similarly, one three-quasineutron configuration, $(-, +)_1^3 = [(+, +)_1 \times (+, -)_1 \times (-, +)_1]_1^3$, can be constructed from the known configurations (fig. 9), and be compared with a known band, the ground-state band, in an odd- A nucleus above the observed band crossing. From the comparison of multiple-quasiparticle states constructed from experimental single-quasiparticle states and the corresponding experimental multiple-quasiparticle states, it can be ascertained whether strong $\hbar\omega$ -dependent or configuration-dependent residual interactions exist between the constituent quasineutrons in the multiple-quasineutron configurations. A premise of the cranked shell model ⁶⁾ is that such residual interactions between quasiparticles are weak.

It also is possible to obtain information on the neutron pairing-correlation parameter, Δ_n , from the comparison of the absolute excitation energies of the constructed and experimental multiple-quasineutron routhians. Since the single-quasiparticle levels usually are referred to the ground-state configuration of the neighbouring even-even nuclei (see subsect. 4.1), it is necessary ⁶⁾ to include, as a constant term, Δ_n in the odd- A routhians. Instead of including, for example, the odd-even mass difference as an estimate of Δ_n into the odd- A routhians, we have chosen to keep Δ_n as a parameter and plot $e' - \Delta_n$ for the odd- A systems. Then the energy difference between the constructed two-quasineutron systems, $e'_{2q.p.} - 2\Delta_n$, and the experimental values in the neighbouring even-even systems, $e'_{2q.p.}$ will give a measure of Δ_n (see figs. 9 and 10). The values of Δ_n obtained from such a comparison will be labelled Δ_n^{cc} to emphasise that they were obtained as a difference between two-quasineutron routhians, constructed as a sum of "experimental" single-quasineutron routhians and "experimental" two-quasineutron routhians. From a similar comparison of the constructed and the experimental three-quasineutron states a measure

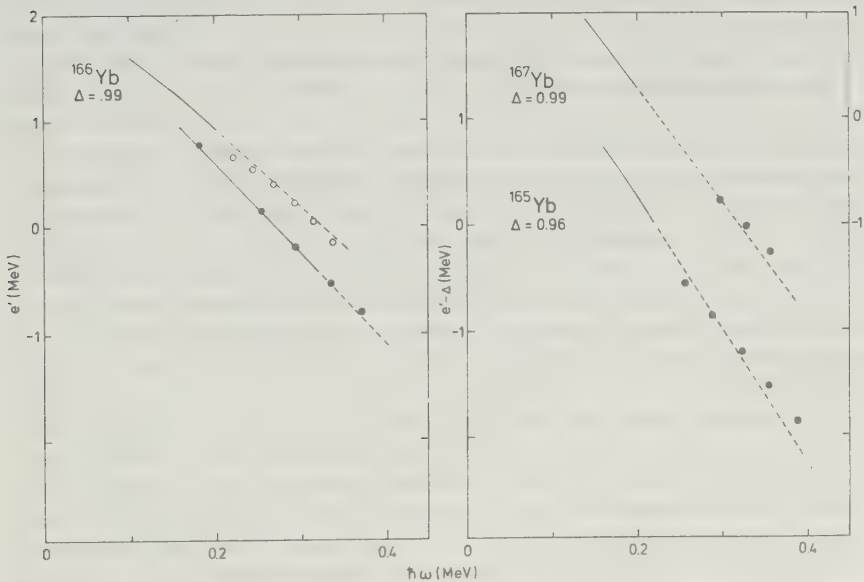


Fig. 10. Comparison of the experimental (circles) and the constructed - see fig. 9 - (solid and dashed lines) routhians for 2- and 3-q. $\bar{n}$ bands in $^{165,166,167}\text{Yb}$. The open and the closed circles for ^{166}Yb represent the experimental routhians for the odd-spin, odd-parity band and the S-band, respectively. The closed circles for $^{165,167}\text{Yb}$ represent the experimental routhians for the $(-, +)_1$ band above backbending. The dashed lines represent the constructed routhians for those ranges of $\hbar\omega$, for which routhians for one or more constituent quasineutrons have been obtained by extrapolation. The energy scales shown to the left-hand and the right-hand sides of the figure for $^{165,167}\text{Yb}$ correspond to ^{165}Yb and ^{167}Yb , respectively. For further details, see text.

of Δ_n also is obtained, since Δ_n enters the constructed three-quasineutron states three times (once in the $e' - \Delta_n$ for each quasineutron – see fig. 9) and only once in the construction of the experimental routhian for the three-quasineutron state.

Constructed two-quasineutron routhians for the $(+, 0)_1^2$ and $(-, 1)_1^2$ states are compared to the experimental ones for ¹⁶⁶Yb in the left-hand side of fig. 10. In the construction of the two-quasineutron routhians average values of the appropriate single-quasineutron routhians in ¹⁶⁵Yb and ¹⁶⁷Yb have been used. Such an averaging should remove, to first order, effects, which vary smoothly with neutron number. In fig. 10 the constructed two-quasineutron routhians (i.e. $e'_{2q.p.} - 2\Delta_n$) have been shifted up by a constant term of $2\Delta_n^{ce} = 1.98$ MeV in order to reproduce the experimental values. Both the slope (i.e. the alignment) and the energy splitting of the experimental routhians for the lowest positive- and negative-parity two-quasineutron configurations are reproduced by routhians constructed as a sum of the routhians of single-quasineutron configurations. Such an agreement between the constructed and the experimental two-quasineutron routhians indicates that a residual interaction between the two unpaired quasineutrons is not strongly dependent upon the angular frequency or the quasiparticle configuration. A residual interaction independent of $\hbar\omega$ and configuration, however, is absorbed in the extracted value of the neutron pairing-correlation parameter, and, therefore, can be extracted by comparison with the neutron odd-even mass difference, Δ_n^{oe} , or the value of Δ_n which reproduces¹⁵⁾ the ground-state band S-band crossing, Δ_n^{CSM} . For ¹⁶⁶Yb, the value of $\Delta_n^{ce} = 0.99$ MeV is somewhat less than $\Delta_n^{oe} = 1.140$ MeV or $\Delta_n^{CSM} = 1.14 \pm 0.03$ MeV, indicating an attractive interaction of about 300 keV between the two unpaired quasineutrons in these configurations. A large portion of the n-n interaction is just the “blocking” of the contributions to pairing by the unpaired quasineutrons. The n-n residual interaction can be compared with the residual proton-neutron interaction estimated [ref. ²⁶⁾] to be about 120 keV from the mass difference between odd-odd and even-even nuclei and the sum of Δ_n^{oe} and Δ_p^{oe} . The reduced value of the p-n residual interaction compared with the n-n residual interaction reflects the small pairing between protons and neutrons in this mass region where protons and neutrons are filling different major shells.

The constructed three-quasineutron routhians for the $(-, +)_1^3$ configuration ($= e'(+, +)_1 + e'(+, -)_1 + e'(-, +)_1$) also are compared to the routhians of the ground-state bands of ¹⁶⁵, ¹⁶⁷Yb above the band crossing. A smaller alignment is observed in the three-quasineutron configurations of both nuclei than is expected from the experimentally constructed routhians. A possible explanation is that when three-quasineutron orbits near the Fermi surface are occupied (thereby “blocking” their contribution to pairing), the pairing is sufficiently reduced to decrease the alignment. Cranked shell-model calculations do indicate that a decrease in alignment is associated with decreased pairing. Therefore, the present agreement in alignments for constructed and experimental two-quasineutron states together with the deviation for the three-quasineutron states would indicate a significant decrease in Δ_n for three-

quasineutron configurations when compared to two-quasineutron configurations. Since there is a deviation between the slopes of the constructed and the experimental three-quasineutron routhians, it is not possible to obtain an estimate of Δ_n from the energy difference between these routhians.

4.4. COMPARISON WITH CRANKED SHELL-MODEL CALCULATIONS

In the mass region, where the Fermi surface is near the low- Ω $i_{13/2}$ neutron orbits, the band-crossing frequency, $\hbar\omega_C$, corresponding to the alignment of the first pair of neutrons, is controlled by a rotational aligned orbit near to the Fermi surface which is particularly sensitive to the neutron pairing-correlation parameter $^{15}\dagger$. From the $\hbar\omega_C$ of the band crossing in the ground-state band of $^{165,167}\text{Yb}$ it, therefore, is possible to obtain an estimate of Δ_n which should be appropriate for other band crossings between one- and three-quasineutron configurations. (The parity, $\pi = -$, of the ground-state band assures that none of the $i_{13/2}$ neutron configurations, $\pi = +$, are "blocked".) The procedure then is to take this value of Δ_n together with deformation parameters, ε_2 and ε_4 , from the systematics predicted by the Lund group 9,28 and the appropriate position of the Fermi surface, λ , to reproduce the neutron number, and to calculate the spectrum of single-particle states in the rotating intrinsic frame. The results of such cranked shell-model (CSM) calculations are shown in fig. 11.

It is possible to directly compare these predicted quasiparticle levels with the experimental routhians constructed (see subsect. 4.1) from the decay scheme information. However, if the "extrapolated" ground-state configuration is taken as the "reference" at all angular frequencies (as was explicitly assumed in the previous sections), it is necessary to reconstruct the pure quasineutron states in the region where there is an interaction between the calculated states. The technique described in refs. 6,29 has been used to obtain the pure quasineutron states in the interaction region and the appropriate resulting theoretical and "experimental" routhians for ^{165}Yb are compared in fig. 12. At angular frequencies below that of the trajectory crossings, the alignment (i.e. slopes of the routhians with respect to $\hbar\omega$) and the relative excitation energies of the lowest positive- and negative-parity trajectories ($(+, +)_1$ and $(-, +)_1$) are well reproduced. In the construction of the experimental routhian the value $\Delta_n = 0.87$ MeV, necessary to reproduce the band crossing in the ground-state band 15 , has been assumed. The energy splitting between the two signatures of the positive-parity trajectories, $(+, +)_1$ and $(+, -)_1$, is greater than

$\dagger$ This is not necessarily always the case, as has been shown for the light Os nuclei 27 , where low-frequency band crossings are controlled by rotational-aligned orbits sufficiently distant from the Fermi surface at low $\hbar\omega$, so that the energy of the orbit relative to the Fermi surface ($\vare_i - \lambda$) is an important component in the quasiparticle energy

$$E_v = \sqrt{\Delta^2 + (\vare_i - \lambda)^2}. \quad (4)$$

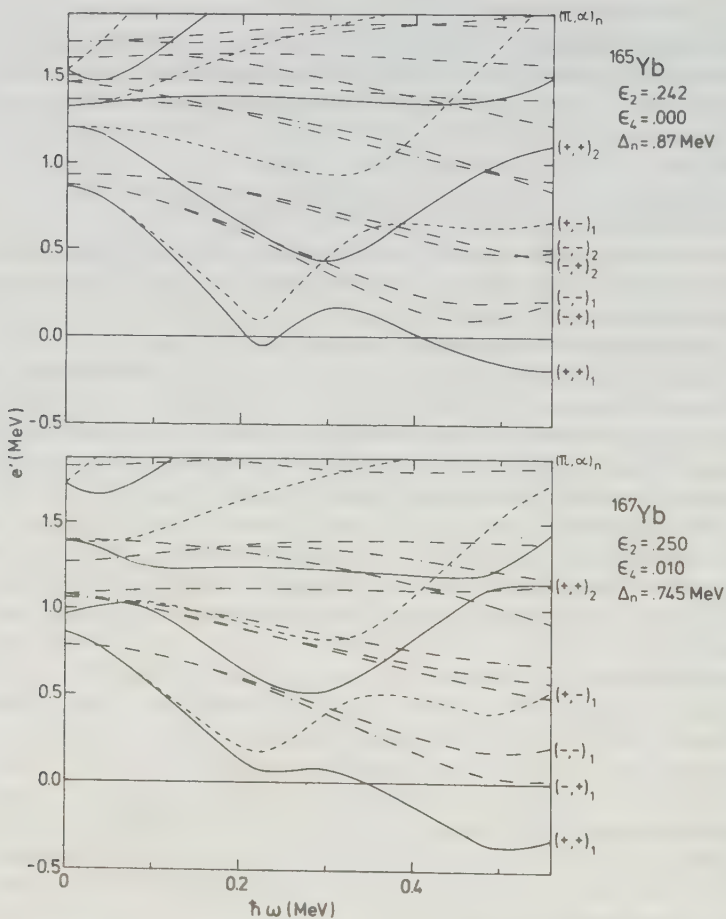


Fig. 11. Quasineutron levels in the rotating frame for $^{165,167}\text{Yb}$, obtained from CSM calculations and shown as a function of the rotational frequency $\hbar\omega$. The parameters used, and the parities and signatures of a few trajectories are shown to the right. $(\pi, \alpha) = (+, +)$, $(+, -)$, $(-, +)$ and $(-, -)$ states are indicated by full drawn, short-dashed, dot-dashed, and long-dashed lines, respectively.

predicted, probably indicating a larger $\Omega = \frac{1}{2}$ component in these configurations than predicted. A similar discrepancy has been observed for several other rare-earth nuclei⁶⁾. The $\hbar\omega$ of the alignment of the first two quasi-neutrons, $\hbar\omega_1$, which corresponds to the crossing of the negative-parity single- and three-quasineutron trajectories, has been fixed in the calculations to reproduce the experimental value by the appropriate choice of Δ_n [ref. ¹⁵⁾]. For $\hbar\omega > \hbar\omega_1$ a larger alignment is theoretically predicted for both negative-parity, three-quasineutron

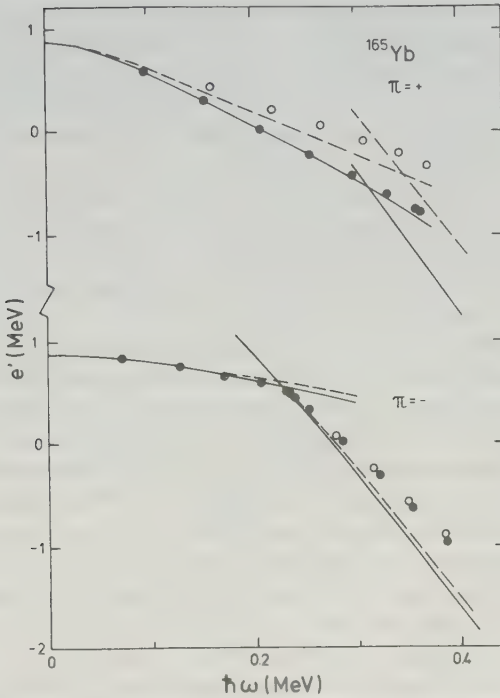


Fig. 12. Comparison of the experimental quasineutron spectra for ^{165}Yb , shown as a function of $\hbar\omega$, with those from CSM calculations. The filled circles and the solid lines are the experimental and the theoretical spectra, respectively, for bands with positive signature. The open circles and the dashed lines depict the same for bands with negative signature. The reference frame used is a Harris parameterization of the ground-state band with $\mathcal{J}_0 = 29.8 \text{ MeV}^{-1} \cdot \hbar^2$ and $\mathcal{J}_1 = 90 \text{ MeV}^{-3} \cdot \hbar^4$.

configurations, $(-, +)_1^3$, and $(-, -)_1^3$ than observed (fig. 12). Such a reduction of the alignment for the $(-, +)_1^3$ configuration relative to the appropriate experimentally constructed three-quasineutron configuration is also noted (see fig. 10) and a reduced pairing in the three-quasineutron configuration has been suggested (subsect. 4.3) as a possible explanation. The alignment of the three-quasineutron configurations can be reproduced in CSM calculations if the pairing-correlation parameter is reduced by about 30% relative to the value of Δ_n^{CSM} obtained from one- and three-quasineutron band crossing frequencies and which reproduces the alignment of the one-quasineutron routhians. Therefore, a total pairing reduction of 45–50% is indicated when the pairing contributions of the $(-, +)_1$, $(+, +)_1$ and $(+, -)_1$ configurations are “blocked”. Even though the alignments of these configurations are not in agreement with CSM predictions, the energy splitting between the two signatures does agree with the calculations.

Band crossings are also predicted in the positive-parity decay sequence (see fig. 12).

corresponding to the alignment of a different pair of $i_{1/2}$ quasineutrons than those responsible for the lower frequency alignment in the negative-parity band and in the yrast band of the neighbouring even- N isotopes. The crossing in the band corresponding to the $(+, +)_1$ configuration, however, is observed ≈ 50 keV higher in $\hbar\omega$ than predicted in the calculations based on the Lund deformation systematics^{9, 28}). It, of course, is possible to increase the frequency of this band crossing in CSM calculations by an arbitrary increase in the pairing-correlation parameter. However, to reproduce the observed crossing frequency, it is necessary to increase Δ_n by about 35% with respect to the value used to reproduce the lower-frequency crossing in the negative-parity band. Such an increased value of Δ_n is as large as that derived from the ground-state band S-band crossing in the neighbouring even- N isotopes¹⁵). It is difficult to understand in a phenomenological way how the occupancy of certain single-particle configurations in odd- N nuclei would significantly reduce Δ_n while others would not affect Δ_n . Therefore, it is felt that factors other than pairing must play a role in the problems of predicting the crossing frequency of the positive-parity band in ^{165}Yb . Indeed the observed crossings in both the negative- and the positive-parity bands of $^{161}, ^{163}\text{Yb}$ are reproduced simultaneously in CSM calculations^{4, 12, 24}), while those in ^{165}Yb are not. The source of the discrepancy in ^{165}Yb is not understood. For example, it is difficult to alter significantly the $\hbar\omega$ difference between the predicted crossings for the negative- and the positive-parity bands by small changes in the ϵ_2 and/or ϵ_4 deformations (Such deformation changes alter the position of the Nilsson states near the Fermi surface.) The frequency of the crossing in the favoured positive-parity band (which corresponds to the exchange of the roles of the $(+, +)_1$ and $(+, +)_2$ trajectories — see fig. 11) represents a more stringent test of the CSM than the lowest-frequency band crossing (i.e. that observed in the negative-parity band). The $(+, +)_1$ – $(+, +)_2$ crossing is sensitive to the quasiparticle energy, alignment, and the interaction of the $(+, +)_2$ trajectory as well as that of the $(+, +)_1$ trajectory. The $(+, +)_2$ trajectory is derived from a Nilsson orbit that is not so near to the Fermi surface, and it interacts with other more highly aligned orbits which are more distant from the Fermi surface (see fig. 11). Therefore, not only the relative positions of the orbits, but also their energy separation from the Fermi surface, i.e. $\epsilon_v - \lambda$ [see eq. (4)], are important in predicting the frequency of the $(+, +)_1$ – $(+, +)_2$ and higher frequency crossings. The strength of the interaction of the $(+, +)_1$ orbit with the vacuum (i.e., with its negative-energy conjugate partner⁶)) which produces the change of slope of this

[†] Recent calculations³⁰) do suggest that the reduction in pairing in odd- N nuclei is dependent on the configuration of the unpaired single particle. For neutron levels in rare-earth nuclei, pairing is reduced more for the negative-parity states than for the positive-parity states and for configurations with smaller signature splitting. Such effects might play a role in explaining the observed discrepancy in the band crossing frequency in the positive-parity band in ^{165}Yb . However, the observed signature splitting between positive-parity states in ^{161}Yb and ^{163}Yb are larger than in ^{165}Yb ; therefore, superficially such an effect would seem to be largest in the lighter odd- N Yb isotopes where the band crossing is predicted at the correct frequency²⁴).

level at the frequency of the band crossing in the negative-parity bands (see fig. 11), also affects the position of the $(+, +)_1 - (+, +)_2$ band crossing.

When the interaction between the quasiparticle trajectories is strong, it becomes difficult to reconstruct the "pure" quasiparticle trajectories in the interaction region. In the case of ^{167}Yb (fig. 11), where there are two strongly interacting trajectory crossings closely spaced in angular frequency (corresponding to the alignment of the first and the second pair of $i_{\frac{1}{2}}$ neutrons), it is particularly difficult to reconstruct "pure" trajectories. Such problems can be circumvented by referring the experimental routhians to the yrast band in the neighbouring even- N isotope. Then the experimental routhians can be compared directly (see fig. 13) to the calculated routhians.

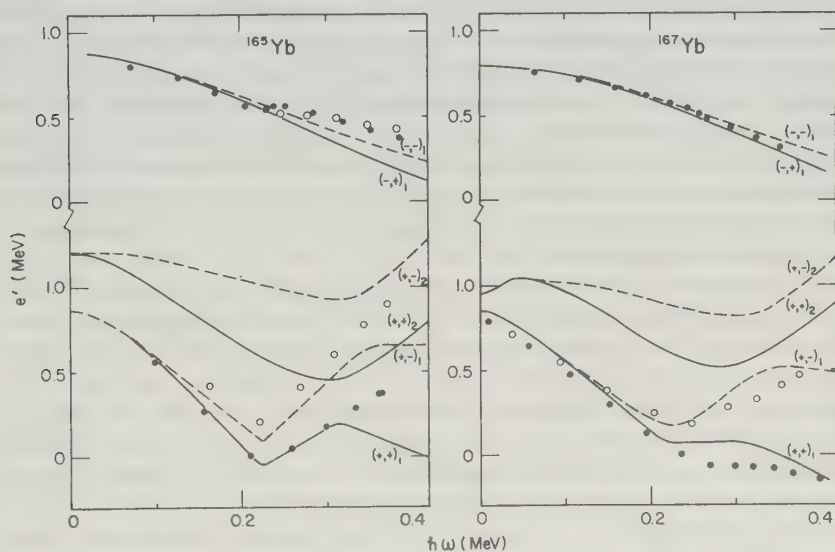


Fig. 13. Theoretical and experimental quasineutron spectra for ^{165}Yb and ^{167}Yb , shown as a function of $\hbar\omega$ and referred to an average of the yrast bands in ^{164}Yb and ^{166}Yb for ^{165}Yb and to the yrast band in ^{168}Yb for ^{167}Yb . The yrast references have been shifted in $\hbar\omega$ so as to make the crossing frequencies of the references coincide with the lowest-frequency crossings in the negative-parity bands in $^{165,167}\text{Yb}$. The open and the closed circles represent the experimental spectra for the negative and the positive signatures, respectively. The quantum numbers appropriate for the theoretical spectra (solid and dashed lines) are also shown in the figure.

In fact, it has been suggested ²¹⁾ that such an approach may be superior, since the interaction at a crossing is never zero and at large angular frequencies the spectrum of quasiparticle levels becomes complicated.

Several practical problems are encountered in referring the odd- N experimental routhians to the yrast band of the neighbouring even- N isotope. Ideally the average routhian of the yrast line from the even- N isotopes with one less and one more

neutron can be constructed as a function of $\hbar\omega$ and subtracted as a reference from the odd- N isotope of interest. It is known, however, that the frequency for the alignment of the first pair of $i_{1/2}$ neutrons is different in odd- N and even- N isotopes¹⁵⁾. Therefore, it is necessary to shift the reference or the experimental vacuum in $\hbar\omega$ so that the crossing frequency of the reference coincides with that in the isotope of interest. (Obvious problems will be encountered if the angular frequency range of interest extends through several yrast band crossings which require different angular frequency shifts.) Besides the shift in the alignment frequency for the first pair of $i_{1/2}$ neutrons, a shift in the magnitude of the alignment associated with this pair of neutrons apparently is observed between the two-quasineutron and the three-quasineutron configuration, presumably also the result of the reduced pairing associated with the larger number of aligned quasiparticles [see subsect. 4.3 and ref. 24)]. Another problem, which must be considered when applying the experimental yrast line as a reference for the neighbouring isotope, is the variation between neighbouring isotopes of the interaction between the constituent bands of the yrast configuration^{9, 10, 31)}. The appropriate treatment for such change in alignment and in the interband interaction strength between the neighbouring even- and odd- N isotopes is not *a priori* obvious. The approach, therefore, is to examine for ^{165}Yb the comparison between the experimental and predicted routhians for both choices of reference frames and then to consider the case of ^{167}Yb where only the reference to the yrast band is appropriate.

When the experimental routhians are referred to the yrast configuration the crossing in the negative-parity bands in $^{165, 167}\text{Yb}$, which corresponds to the low frequency $i_{1/2}$ neutron alignment, should disappear (compare figs. 12 and 13). This alignment also appears in the even- N yrast band reference. Therefore, a test of the reference frame depends on whether the resulting routhians of the negative-parity bands are smooth in the region of the low-frequency band crossing. A "glitch" appears in the experimental routhian of the $(+, +)_1$ band[†] in ^{165}Yb at the crossing frequency and the slope of both the negative-parity bands, $(-, +)_1$ and $(-, -)_1$ is less than predicted for $\hbar\omega > \hbar\omega_c$ (see fig. 13). These features presumably are associated with the problem of referring the routhians to the yrast bands of the even- N neighbours with pairing correlations and interband interactions which are not completely appropriate to ^{165}Yb . The discrepancy between the predicted and the observed alignments of the negative-parity states of ^{165}Yb (see fig. 12) appears as a slope change of the experimental routhian in the yrast-reference representation (see fig. 13). The difference between the predicted and the observed energy splitting of the $(+, +)_1$ and $(+, -)_1$ configurations (signature splitting) and the discrepancy in the crossing frequencies for these positive-parity band both can be observed (fig. 13) in

[†] In the representation of the quasiparticle relative to the yrast configuration, the configurations are labelled by the non-yrast excited quasiparticles²¹⁾. For examples, the ground-state bands of $^{165, 167}\text{Yb}$ will be $(+, +)_1$ both below and above the band crossing, since the $i_{13/2}$ neutrons also become aligned in the reference.

the yrast-reference representation, even though a slope change is introduced into the routhians, which is the result of the ground-state band S-band crossing in the even- N yrast reference.

The ^{167}Yb experimental routhians, shown in fig. 13, are referred to the yrast band of ^{168}Yb [refs. ^{20, 32}]. A constant value of $E_v = 0.79$ MeV has been included in the routhian. This value corresponds to $\Delta_n = 0.745$ MeV plus a contribution from $\epsilon_v\lambda$ [see eq. (4)], which accounts for the fact that the Fermi surface in ^{167}Yb is located in a gap in the Nilsson levels (fig. 8). Had the ^{166}Yb yrast band, with its weak ground-state band S-band interaction, been used as a reference for ^{167}Yb , with its strong interaction between the ground-state band and its crossing band, then a pronounced “glitch” would have appeared in the negative-parity band at the crossing frequency. Similarly, the large S-band alignment in ^{166}Yb would have led to a slope change in the ^{167}Yb negative-parity band above the band crossing frequency. With the reasonably smooth routhians of the negative-parity band of ^{167}Yb in the frequency region of the $i_{13/2}$ neutron alignment and the agreement between the experimental and the predicted routhians for this band, we proceed to the discussion of the more structured routhians for the positive-parity configurations of ^{167}Yb with some conviction that the ^{168}Yb yrast configuration is a reasonable reference for ^{167}Yb . The routhians of the positive-parity configurations are at low $\hbar\omega$ lower in excitation energy than predicted, indicating either that the predicted energy separation between the $\frac{5}{2}^-$ [523] and the $\frac{5}{2}^+$ [642] Nilsson configurations is too great or that the Fermi surface should be closer to the $\frac{7}{2}^+$ [633] Nilsson state than to the $\frac{5}{2}^+$ [642] state (see fig. 8). Similar to ^{165}Yb and other 6) odd- N rare-earth nuclei, the signature splitting between the $(+, +)_1$ and the $(+, -)_1$ configurations is observed to be larger than predicted. Contrary to the case of ^{165}Yb , the crossing in the $(+, +)_1$ band, corresponding to the alignment of the second combination of $i_{13/2}$ neutrons[†] (i.e. the exchange of character of the $(+, +)_1$ and the $(+, +)_2$ configurations²¹) is close to the predicted frequency. This crossing, which corresponds to the change in slope of the $(+, +)_1$ routhian at $\hbar\omega \approx 0.32$ MeV, is characteristic of strongly interacting configurations in agreement with the predictions. The band crossing in the $(+, -)_1$ band, corresponding to an exchange in character of the $(+, -)_1$ and the $(+, -)_2$ configurations, is not observed up to $\hbar\omega \approx 0.375$ MeV, whereas it is predicted at a lower angular frequency (see fig. 13). The alignment in the $(+, -)_1$ band apparently is starting to increase at the last observed transition, $\hbar\omega \approx 0.375$ MeV (see fig. 7). The crossings of the $(+, +)_1$ and $(+, -)_1$ bands are at different angular frequencies in contrast to the situation for the lighter Yb isotopes⁸) where these crossings are found at nearly equal frequencies. This feature probably is connected to the low- Ω components, with an associated large alignment, which mixes into the $(+, +)_1$

[†] The alignment of the pair of $i_{13/2}$ neutrons which is responsible for the low-frequency band crossing in the negative-parity band of ^{167}Yb and the ground-state band S-band crossing in the even- N isotopes is not allowed by the Pauli principle (i.e. “blocked”) since the lowest even-parity quasineutron orbit $(+, +)_1$ is occupied.

quasineutron for $N \geq 95$, thereby depressing the $(+, +)_2$ trajectory with respect to the $(+, -)_2$ trajectory (see fig. 11). For the lower-mass Yb isotopes, the highly aligned low- Ω trajectories are near the Fermi surface. Even though the CSM calculations give a qualitative description of the crossing frequencies and the interaction strengths in the $(+, +)_1$ band, the details of the routhian are not reproduced (see fig. 13).

4.5. INTERBAND M1 TRANSITIONS

The interband M1-transition matrix elements connecting states in rotational bands based on the opposite signatures of high- j , low- Ω quasiparticle orbits are predicted ³³) to be strongly signature dependent even for small rotational frequencies. The M1 transitions between bands based on the $(+, +)_1$ and $(+, -)_1$ configurations in light odd- N Yb nuclei provide an excellent test of these predictions, since these bands are strongly populated in (Hf, xn) reactions. In fact, such transitions in ¹⁶¹Yb [refs. ^{4, 34})] were used as the original example of this effect. The interband transitions between the $(+, +)_1$ and $(+, -)_1$ bands in ^{165, 167}Yb provide an even more sensitive test of the signature-dependent rotational effect on the M1 transitions. Not only are more transitions observed in ¹⁶⁷Yb than in ¹⁶¹Yb, but in ¹⁶⁵Yb the signature splitting in energy is such that the $I-1$ state in the $(+, -)_1$ band is nearly degenerate with the I state in the $(+, +)_1$ band (see fig. 3). This is exactly the condition for the M1-transition matrix elements for $(I+1, \alpha = -\frac{1}{2} \rightarrow I, \alpha = \frac{1}{2})$ transitions to approach zero, and for that of the $(I, \alpha = \frac{1}{2} \rightarrow I-1, \alpha = -\frac{1}{2})$ transitions to have the maximum enhancement ³³). For example, $B(M1, \frac{23}{2}^+ \rightarrow \frac{21}{2}^+)$ should be very small and $B(M1, \frac{21}{2}^+ \rightarrow \frac{19}{2}^+)$ is expected to be large. In ¹⁶⁵Yb, the γ -ray energies of the $(I, \alpha = \frac{1}{2} \rightarrow I-1, \alpha = -\frac{1}{2})$ transitions in the $i_{13/2}$ band are so small that these transitions cannot compete with the strongly-enhanced $I \rightarrow I-2$ transitions along the yrast cascade. The $(I+1, \alpha = -\frac{1}{2} \rightarrow I, \alpha = \frac{1}{2})$ transitions, which should be greatly hindered, however, are observed. In ¹⁶⁷Yb, where the signature splitting is smaller, both types of M1 transitions between the positive-parity bands are observed.

Even though no absolute transition rates have been measured, some information on the M1 matrix elements can be extracted by a comparison to the E2 strength which is assumed to follow the pattern of rigid rotation[†]. From the experimental branching ratios $\lambda = \Gamma_\gamma(I \rightarrow I-2)/\Gamma_\gamma(I \rightarrow I-1)$, a value of

$$\frac{B(M1)}{Q_0^2} = \frac{E_{\gamma 1}^2}{14.41} \left[\left(\frac{E_{\gamma 2}}{E_{\gamma 1}} \right)^5 \langle IK20|I-2K \rangle^2 \frac{1}{\lambda} - \langle IK20|I-1K \rangle^2 \right]$$

can be extracted. It is also possible to use the experimental values of the mixing

[†] Rotational perturbations on the $B(E2)$ values for the $I \rightarrow I-1$ transitions between the signature partners and for in-band $I \rightarrow I-2$ transitions are expected to be quite small ³³).

ratios δ within the $I \rightarrow I-1$ transitions to determine the same ratio

$$\frac{B(M1)}{Q_0^2} = \frac{E_{\gamma 1}^2}{14.41} \frac{\langle IK20|I-1K \rangle^2}{\delta^2}.$$

In both expressions $E_{\gamma 1}$ and $E_{\gamma 2}$ correspond to the energies in keV for the $I \rightarrow I-1$ and the $I \rightarrow I-2$ transitions respectively. The data presented in fig. 14 have been

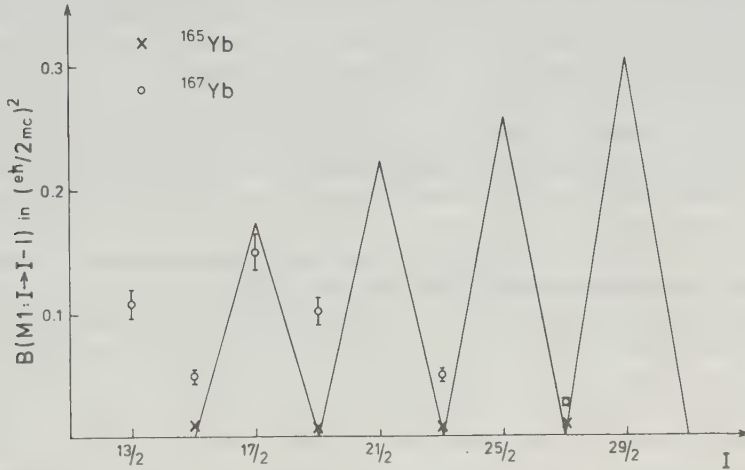


Fig. 14. $B(M1)$ values for $I \rightarrow I-1$ transitions between states of opposite signature of the $i_{13/2}$ band in $^{165,167}\text{Yb}$. These values were derived, using $Q_0 = 7 e \cdot b$ and the average value of $K = 2$ (see text). The zigzag line shows the theoretical values appropriate for the nucleus ^{165}Yb , calculated from the particle-rotor model ³³⁾.

derived, assuming a value of $Q_0 = 7 e \cdot b$. For both nuclei studied, $K = \frac{5}{2}$ was used in extracting values of $B(M1)/Q_0^2$. Since the rotation is expected to mix lower K -values into the wave function, values of $K = \frac{3}{2}$ and $\frac{1}{2}$ were also applied and were found to increase the $B(M1)$ values extracted from the branching ratio λ , while the $B(M1)$ values obtained from the mixing ratio δ were found to decrease drastically if $K = \frac{3}{2}$ or $\frac{1}{2}$ are assumed. The experimental determination of δ involves a larger uncertainty than that of the λ -values, but, in order to bring the two extracted values of $B(M1)$ into agreement, the average value of K has to be shifted to $\approx \frac{1}{2}$ unit below $\frac{5}{2}$. The values presented in fig. 14 have been derived from the branching ratios with this K -admixture taken into account. The effect is found to be largest on the highly retarded $B(M1)$ values in ^{165}Yb .

The agreement with the $B(M1)$ transition rates calculated for ^{165}Yb using the particle-rotor model ³³⁾ is excellent (see fig. 14). It, of course, would be important to

determine the M1 transition rates for the enhanced $I, \alpha = \frac{1}{2} \rightarrow I-1, \alpha = -\frac{1}{2}$ M1 transitions. For ^{167}Yb , the separation between the $B(\text{M1})$ values for the transitions between the two signatures is observed, but in this nucleus the retardation of the $I+1, \alpha = -\frac{1}{2} \rightarrow I, \alpha = \frac{1}{2}$ M1 transitions is less, as is also expected, since the Fermi surface here lies further away from the low- Ω orbits of the $i_{11/2}$ configuration.

5. Summary

The nuclei $^{165, 167}\text{Yb}$ are well-deformed nuclei with $\varepsilon_2 \approx 0.25$ and very small ε_4 . The present study identifies the ground-state bands based on the $[523]_{\frac{5}{2}}^-$ Nilsson orbital to spins $\frac{53}{2}^-$ and $\frac{49}{2}^-$ for ^{165}Yb and ^{167}Yb respectively, thereby extending the knowledge of the negative-parity bands to well above the backbending region. The $\alpha = -\frac{1}{2}$ signature of the $[523]_{\frac{5}{2}}^-$ band has been identified in the case of ^{165}Yb above backbending. The favoured and the unfavoured members of the $i_{11/2}$ band have been established to high spin values, $\frac{49}{2}^+$ and $\frac{39}{2}^+$ for ^{165}Yb and $\frac{53}{2}^+$ and $\frac{43}{2}^+$ for ^{167}Yb , respectively.

The present study can be regarded as a test case for the cranked shell model in a region of stable deformation. Routhians and alignments have been extracted from the experimental data. Experimental single-quasineutron routhians have been used to construct two- and three-quasineutron routhians. The $\hbar\omega$ and configuration dependence of the constructed routhians for two-quasineutron configurations in ^{166}Yb agree with the experimental data, suggesting that the residual interaction between two unpaired quasineutrons is only weakly dependent upon the configuration and frequency. A comparison of the magnitude of the neutron pairing-correlation parameter obtained from the energy difference between the two-quasineutron routhians and the sum of the constituent single-quasineutron routhians with the neutron odd-even mass difference and the pairing-correlation parameter obtained from the $\hbar\omega_c$ of the band crossing in the ^{166}Yb yrast sequence gives a residual interaction of about 300 keV between the unpaired quasineutrons. The dominating portion of the n-n residual interaction is thought to be the "blocking" of the pairing contributions of the unpaired quasineutrons. The experimental alignments of the negative-parity three-quasineutron configurations, $(-, +)_1^3$ and $(-, -)_1^3$, is less than those from either the sum of experimental single-quasineutron alignments or from CSM calculations assuming the Δ_n , which reproduces the correct frequency of the band crossing in the negative-parity bands. This indicates a further reduction of pairing for the seniority-three states. Although CSM calculations yield correct signature splitting for the negative-parity bands in ^{165}Yb , it fails to account for either the signature splitting in the positive-parity band or the band-crossing frequencies in the positive-parity decay sequences in ^{165}Yb . The source of these discrepancies is not understood, but may be associated with the interactions between the positive-parity quasineutron configurations in the CSM.

The signature dependence of the interband-intraband branching ratios as well as of the interband M1/E2 mixing ratios provides an experimental justification of the signature dependence of the $B(M1)$ transition rates suggested by Hamamoto³³⁾.

We are grateful to Prof. O. C. Kistner for communicating to us the level schemes of ^{167, 168}Yb prior to publication. Discussions with Dr. I. Hamamoto and Dr. R. Bengtsson are acknowledged, as is the financial support from the Nordic Committee for Accelerator Based Research and the Danish Natural Science Research Council.

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HIGH-SPIN PROPERTIES OF ^{163}Yb : BAND CROSSINGS AND SIGNATURE-SPLITTING IN Yb NUCLEI

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Received 26 July 1982

Abstract: High-spin states in ^{163}Yb have been studied by the $^{149}\text{Sm}(^{18}\text{O}, 4n)^{163}\text{Yb}$ reaction with 84 MeV ^{18}O ions from the NBI tandem accelerator. Gamma-gamma coincidence data were accumulated with an array of five Compton-suppressed Ge(Li) detectors resulting in an extension of our knowledge of high spin members of familiar rotational bands as well as of weakly populated side bands. A $\gamma\gamma$ time coincidence experiment, conversion electrons and angular distribution measurements were performed. Four side bands are observed besides the yrast cascade, which is followed up to its $\frac{49}{2}^{+}$ member. The yrast band of the ^{163}Yb nucleus has been interpreted, following the systematics in this region of neutron deficient rare-earth nuclei, as the favoured member of a decoupled $i_{13/2}$ neutron band. The negative-parity band $(-, +)_1$ based on the $\frac{3}{2}^{-}$ [521] state was reestablished. The other signature of this band is the newly introduced band $(-, -)_1$. The signature splitting in the negative-parity band is observed to be small; however, for large $\hbar\omega$, band $(-, -)_1$ lies lower in energy than band $(-, +)_1$, which is a unique observation in this mass region. The quasi-particle routhians and alignments obtained from these data are compared with results of cranked shell-model calculations and similar data for the heavier and lighter Yb nuclei. The rotational effects on M1 transitions connecting unfavoured members of the band, based on the $i_{13/2}$ orbital, with the favoured members are demonstrated.

E NUCLEAR REACTIONS $^{149}\text{Sm}(^{18}\text{O}, 4n)$, $E = 84$ MeV; measured $\gamma\gamma$ -coin, $\gamma(\theta)$, $I(\text{ce})$. ^{163}Yb deduced levels, J , π , yrast transitions, spin alignments, band crossings, routhians, γ -branching ratios. Enriched targets, Compton suppressed Ge(Li) array detectors. Cranked shell model.

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1. Introduction

The present study of ^{163}Yb is one in a series of spectroscopic studies¹⁻⁶⁾ of near-yrast high-spin states in light Yb isotopes. Two new decay sequences are established, and two of the known⁷⁾ decay sequences are extended to higher angular momenta. Systematic data, therefore, are now available for several decay sequences in ^{161}Yb , ^{163}Yb , ^{165}Yb , and ^{167}Yb . The present article discusses the systematics of band crossing frequencies and signature-dependent splitting of band crossing frequencies and signature-dependent splitting in excitation energies and M1 transition rates in these nuclei. A brief review of the relation between the decoupling in excitation energy and M1 transition rates of $K = \frac{1}{2}$ bands⁸⁾ and the observed signature splitting in these parameters is also presented. Intrinsic excitation energies (routhians) and M1-transition rates are compared with cranked shell-model⁹⁾ and particle-rotor-model¹⁰⁾ calculations. Some of the preliminary results of this study have been presented in references^{11,12)}.

2. Experimental methods

Ytterbium-163 was produced with the $^{149}\text{Sm}(^{18}\text{O}, 4n)$ reaction using an 84 MeV beam of ^{18}O from the Niels Bohr Institute FN tandem accelerator. The target was a metallic ^{149}Sm (97.7%) foil with a thickness of 1.5 mg/cm² backed by ~ 2 mg/cm² ^{208}Pb to stop the recoils. For conversion electron measurements (660–1000) $\mu\text{g}/\text{cm}^2$ thick targets were used. The following experimental studies have been performed:

(i) For coincidence measurements, γ -rays were detected with an array of five Compton-suppressed Ge(Li) detectors¹³⁾. This setup reduces the background by about a factor of 3 thereby making it possible both to identify weak transitions in the gated spectra, and to gate on weak transitions. Examples of coincidence spectra, representative for bands observed in the ^{163}Yb nucleus, are shown in fig. 1.

(ii) The relative intensities of the γ -rays were measured at six angles between 0° and 90° with respect to the incident beam direction. The beam was stopped by a 0.3 mm lead foil inside the target chamber to allow measurements in the forward direction. A single low-energy photon detector of small volume and a Compton-suppressed Ge(Li) detector were used for measuring simultaneously two sets of singles γ -ray spectra. The observed angular distributions are fitted with the expression

$$W(\theta) = A_0 + A_2 P_2(\cos \theta) + A_4 P_4(\cos \theta) \quad (1)$$

following the normalization of each spectrum to the intense peaks recorded in the third monitor detector placed below the target chamber at a fixed angle (90°). The results of the angular distribution data are summarized in table 1.

(iii) In order to study low-energy transitions $\sim 20 \lesssim E_\gamma \lesssim 300$ keV in ^{163}Yb , a $\gamma\gamma$ time coincidence experiment was performed with one intrinsic Ge detector sensitive in the X-ray energy range and four big Ge(Li) detectors with matched gains. A

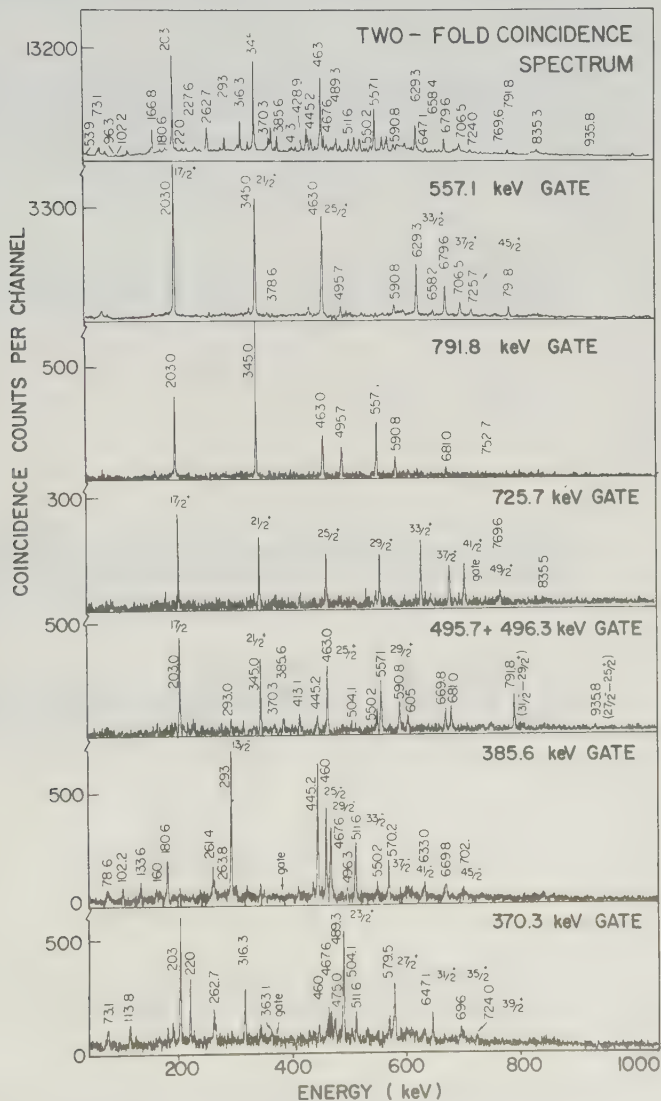


Fig. 1. Background corrected $\gamma\gamma$ coincidence spectra for the bands in ^{163}Yb . Representative gates for each of the observed bands are selected.

TABLE 1

The γ -ray energies, intensities, electron conversion and angular distribution coefficients and quadrupole-dipole mixing ratios for transitions assigned to ^{163}Yb in the $^{149}\text{Sm}(^{18}\text{O}, 4n)$ reaction at 84 MeV

E_γ (keV)	I_γ^{el}	$\alpha \times 10^4$	Ang. distr. coeff.		$\delta(Q/D)$ mixing ratio	Multi- polarity $b)$	Assignment $b)$ $I_i^+ \rightarrow I_f^+$	$E_i \rightarrow E_f$ (keV)
			A_2/A_0	A_4/A_0				
43.6	*						$\frac{13}{2}^+ \rightarrow \frac{9}{2}^+$	167.4 $\rightarrow$ 123.8
53.9	91.8		-0.28(01)	0.27(01)	~ 1.5	M1/E2	$\frac{9}{2}^+ \rightarrow \frac{5}{2}^+$	53.9 $\rightarrow$ 0
78.6	11.3		-0.12(10)	0.22(20)	0.03	M1	$\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$	132.5 $\rightarrow$ 53.9
96.3	1.0 a		0.52(30)	-0.23(20)	0.4	M1/E2	$\frac{11}{2}^+ \rightarrow \frac{13}{2}^+$	263.7 $\rightarrow$ 167.4
102.0	2.6		0.27(20)	0.16(30)	0.4	M1/E2	$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$	234.5 $\rightarrow$ 132.5
113.3	2.5		0.30(08)	0.30(18)	0.5	M1/E2	$\frac{13}{2}^+ \rightarrow \frac{17}{2}^+$	483.7 $\rightarrow$ 370.4
133.5	2.8		0.05(03)	-0.33(04)		M1/E2	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	527.5 $\rightarrow$ 394.0
138.6	1.0 a						$\frac{15}{2}^+ \rightarrow \frac{21}{2}^+$	854.0 $\rightarrow$ 715.4
139.9	1.0 a		0.89(10)	0.24(11)	1.2	M1/E2	$\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$	263.7 $\rightarrow$ 123.8
159.5	2.4		-0.07(20)	-0.16(20)		M1	$\frac{11}{2}^+ \rightarrow \frac{9}{2}^+$	394.0 $\rightarrow$ 234.5
162.5	~ 0.5						$\frac{31}{2}^- \rightarrow \frac{27}{2}^-$	2527.3 $\rightarrow$ 2364.8
180.6	3.5		0.28(03)	-0.12(03)		E2	$\frac{9}{2}^- \rightarrow \frac{5}{2}^-$	234.5 $\rightarrow$ 53.9
203.0	100.0		0.31(04)	-0.10(04)		E2	$\frac{17}{2}^+ \rightarrow \frac{13}{2}^+$	370.4 $\rightarrow$ 167.1
220.0	2.5		0.20(03)	0.00(03)		E2	$\frac{15}{2}^+ \rightarrow \frac{11}{2}^+$	483.7 $\rightarrow$ 263.7
227.6	2.8		-0.36(15)	0.24(15)		(E1)	$\frac{33}{2}^- \rightarrow \frac{29}{2}^-$	2797.5 $\rightarrow$ 2569.9
261.5	1.3		0.32(02)	-0.09(02)		E2	$\frac{11}{2}^- \rightarrow \frac{7}{2}^-$	394.0 $\rightarrow$ 132.5
263.8	3.3 c		-0.24(04)	-0.07(04)		(E1)	$\frac{13}{2}^- \rightarrow \frac{9}{2}^-$	527.5 $\rightarrow$ 263.7
293.0	9.2		0.31(05)	-0.10(06)		E2	$\frac{1}{2}^- \rightarrow \frac{3}{2}^-$	527.5 $\rightarrow$ 234.5
316.3	3.9		0.51(04)	0.15(05)	0.65	M1/E2	$\frac{13}{2}^+ \rightarrow \frac{13}{2}^+$	483.7 $\rightarrow$ 167.4
345.0	85.0	1200(200)	0.32(04)	-0.09(04)		E2	$\frac{29}{2}^+ \rightarrow \frac{27}{2}^+$	715.4 $\rightarrow$ 370.4
363.1	3.2	370 assumed	-0.05(14)	-0.24(11)		(E1)	$\frac{29}{2}^- \rightarrow \frac{27}{2}^-$	2285.9 $\rightarrow$ 1922.8
370.3	13.0		0.33(01)	-0.03(01)		E2	$\frac{19}{2}^+ \rightarrow \frac{17}{2}^+$	854.0 $\rightarrow$ 483.7
378.7	~ 1.3		-0.38(20)			(E1)	$\frac{27}{2}^- \rightarrow \frac{25}{2}^-$	2114.2 $\rightarrow$ 1735.5
385.6	11.6		0.30(07)	-0.11(08)		E2	$\frac{17}{2}^- \rightarrow \frac{15}{2}^-$	913.1 $\rightarrow$ 527.5
413.1	3.2		0.28(03)	-0.22(04)		E2	$\frac{31}{2}^+ \rightarrow \frac{27}{2}^+$	2527.3 $\rightarrow$ 2114.2
429.4	1.8		0.07(06)	-0.08(06)		(E1)	$\frac{17}{2}^- \rightarrow \frac{17}{2}^-$	913.1 $\rightarrow$ 483.7
445.0	11.5		0.32(05)	-0.10(06)		E2	$\frac{21}{2}^+ \rightarrow \frac{17}{2}^+$	1358.1 $\rightarrow$ 913.1
460.2	12.2	225(60)	0.34(05)	-0.10(06)		E2	$\frac{23}{2}^- \rightarrow \frac{21}{2}^-$	1818.3 $\rightarrow$ 1358.1
463.0	83.8	131(30)	0.32(03)	-0.09(04)		E2	$\frac{23}{2}^+ \rightarrow \frac{21}{2}^+$	1178.4 $\rightarrow$ 715.4
467.6	15.0		0.29(03)	-0.07(03)		E2	$\frac{29}{2}^- \rightarrow \frac{25}{2}^-$	2285.9 $\rightarrow$ 1818.3
472.8	~ 2.0						$\frac{27}{2}^- \rightarrow (\frac{23}{2}^-)$	2114.2 $\rightarrow$ 1641.4

475.0	4.5	-0.23(06)	0.04(06)	(E1)	$\frac{25}{2}^- \rightarrow \frac{23}{2}^+$	1818.3 $\rightarrow$ 1343.2
483.6	3.0 ^{a)}	0.44(13)	0.24(14)	M1/E2	$\frac{19}{2}^+ \rightarrow \frac{17}{2}^+$	854.0 $\rightarrow$ 370.4
489.3	15.2 ^{c)}	0.35(05)	-0.11(05)	E2	$\frac{23}{2}^+ \rightarrow \frac{19}{2}^+$	1343.3 $\rightarrow$ 854.0
495.7	4.0	0.24(04)	-0.12(04)	E2	$\frac{31}{2}^- \rightarrow \frac{27}{2}^-$	3023.0 $\rightarrow$ 2527.3
496.3	1.5	0.25(15)	-0.15(16)	E2	$\frac{23}{2}^- \rightarrow \frac{21}{2}^-$	2524.2 $\rightarrow$ 2027.9
504.1	2.0 ^{a)}	0.12(09)	-0.05(09)	(E1)	$\frac{21}{2}^- \rightarrow \frac{19}{2}^-$	1358.1 $\rightarrow$ 854.0
511.6	15.7 ^{a)}	0.53(10)	-0.03(10)	E2	$\frac{33}{2}^- \rightarrow \frac{29}{2}^-$	2797.5 $\rightarrow$ 2285.9
550.2	2.0 ^{a)}	0.31(03)	-0.06(08)	(E2)	$\frac{33}{2}^- \rightarrow \frac{29}{2}^-$	3074.4 $\rightarrow$ 2524.2
557.1	55.5	0.40(05)	-0.02(05)	E2	$\frac{29}{2}^+ \rightarrow \frac{27}{2}^+$	1735.5 $\rightarrow$ 1178.4
570.2	15.1 ^{a)}	0.29(06)	-0.12(06)	E2	$\frac{37}{2}^- \rightarrow \frac{33}{2}^-$	3367.7 $\rightarrow$ 2797.5
579.5	10.6 ^{a)}	0.40(05)	-0.10(05)	E2	$\frac{27}{2}^+ \rightarrow \frac{25}{2}^+$	1922.8 $\rightarrow$ 1343.3
590.8	5.7 ^{a)}	0.16(18)	-0.20(18)	E2	$\frac{39}{2}^- \rightarrow \frac{35}{2}^-$	3613.8 $\rightarrow$ 3023.0
605.0	1.9	0.30(04)	-0.09(05)	(E2)	$\frac{37}{2}^- \rightarrow \frac{33}{2}^-$	3679.4 $\rightarrow$ 3074.4
629.3	43.7	0.36(06)	-0.13(04)	E2	$\frac{33}{2}^+ \rightarrow \frac{29}{2}^+$	2364.8 $\rightarrow$ 1735.5
633.0	6.7	0.12(03)	-0.07(03)	E2	$\frac{41}{2}^- \rightarrow \frac{37}{2}^-$	4000.7 $\rightarrow$ 3367.7
647.1	6.7	-0.38(08)	-0.04(08)	E1	$\frac{35}{2}^- \rightarrow \frac{31}{2}^-$	2569.9 $\rightarrow$ 1922.8
658.2	3.8	0.39(04)	-0.05(05)	E2	$\frac{35}{2}^- \rightarrow \frac{31}{2}^-$	3023.0 $\rightarrow$ 2364.8
669.8	3.0 ^{a)}	0.23(03)	-0.09(03)	E2	$\frac{37}{2}^- \rightarrow \frac{33}{2}^-$	2027.9 $\rightarrow$ 1358.1
679.6	22.1	0.37(29)	-0.19(20)	E2	$\frac{43}{2}^- \rightarrow \frac{39}{2}^-$	3044.4 $\rightarrow$ 2364.8
681.0	~ 4.0	0.45(22)	-0.24(24)	E2	$\frac{43}{2}^- \rightarrow \frac{39}{2}^-$	4294.8 $\rightarrow$ 3613.8
696.0	5.0 ^{c)}	0.34(08)	-0.12(08)	E2	$\frac{41}{2}^+ \rightarrow \frac{37}{2}^+$	3265.9 $\rightarrow$ 2569.9
702.0	3.0	0.44(20)	-0.20(18)	E2	$\frac{41}{2}^+ \rightarrow \frac{37}{2}^+$	4702.7 $\rightarrow$ 4000.7
706.5	15.6	0.12(08)	-0.10(08)	(E2)	$\frac{43}{2}^- \rightarrow \frac{39}{2}^-$	3750.9 $\rightarrow$ 3044.2
724.0	1.9	0.50(25)	0.13(20)	E2	$\frac{43}{2}^- \rightarrow \frac{39}{2}^-$	3989.9 $\rightarrow$ 3265.9
725.7	5.6	0.38(22)	0.05(07)	E2	$\frac{43}{2}^- \rightarrow \frac{39}{2}^-$	4476.6 $\rightarrow$ 3750.9
752.7	~ 1.9	-0.31(07)	-0.22(25)	(E2)	$\frac{47}{2}^- \rightarrow \frac{43}{2}^-$	5047.5 $\rightarrow$ 4294.8
769.6	3.6	0.60(28)	0.15(15)	E1	$\frac{49}{2}^+ \rightarrow \frac{45}{2}^+$	5246.2 $\rightarrow$ 4476.6
791.8	9.7	-0.36(25)	0.15(15)	(E2)	$\frac{49}{2}^+ \rightarrow \frac{45}{2}^+$	2527.3 $\rightarrow$ 1735.5
835	~ 3.3	-0.38(14)	-0.02(14)	E1	$\frac{49}{2}^+ \rightarrow \frac{45}{2}^+$	6081.5 $\rightarrow$ 5246.2
926.0	2.0				$\frac{49}{2}^+ \rightarrow \frac{45}{2}^+$	1641.4 $\rightarrow$ 715.4
935.8	4.3				$\frac{47}{2}^- \rightarrow \frac{43}{2}^-$	2114.2 $\rightarrow$ 1176.4

^{a)} Intensity determined from coincidence relation.

^{b)} The assignments given in parentheses are uncertain.

^{c)} The intensity contains also the contribution from other lines (also from other nuclei).

* Rough estimation of the γ -ray relative intensities in the 40 keV region is showing the intensity ratios:

$$I_{41.0} : I_{43.6} : I_{45.3} : I_{53.9} : I_{203.0} = 7 : 0.8 : 1.6 : 0.9 : 1.$$

The 41.0 and 45.3 we ascribed to deexcite 99.1 keV level (see text, sect. 3.1).

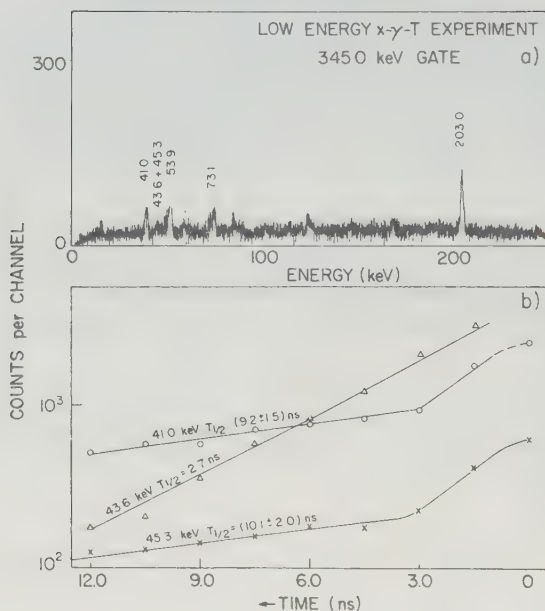


Fig. 2. (a) Coincidence spectrum recorded in the X-ray detector obtained by gating on the 345 keV γ -ray, a member of the yrast band. (b) Decay curves for γ -rays succeeding the $\frac{13}{2}^+$ state of the yrast band.

multiplicity filter of four 7.6 cm $\times$ 7.6 cm NaI(Tl) detectors was also used. In the present experiment the time-to-amplitude converter was started by a pulse corresponding to the detection of an event in the X-ray detector and stopped by a delayed pulse from the γ -ray detectors. The relevant results of this low-energy coincidence experiment are shown in fig. 2.

(iv) The conversion electron spectra were measured with a mini-orange electron spectrometer, to determine conversion coefficients of selected transition. The energy regions $150 \lesssim E_e \lesssim 300$ keV, $300 \lesssim E_e \lesssim 900$ keV, and $500 \lesssim E_e \lesssim 1200$ keV were selected by using appropriate magnet configurations. In order to reduce the background of unwanted events only electrons in coincidence with a multiplicity filter consisting of the four NaI(Tl) detectors were recorded. Gamma-spectra gated by the same multiplicity filter were also recorded simultaneously with a Ge(Li) detector. The variation of the transmission with the electron energy of the mini-orange spectrometer was determined in a supplementary experiment using continuous β -ray sources¹⁴). Relative K conversion coefficients, determined from electron and γ -ray peak areas after corrections for the relative efficiencies of both detectors, were normalized to $\alpha_K = 3.7 \times 10^{-2}$ for the 345.0 keV ($\frac{21}{2}^+ \rightarrow \frac{17}{2}^+$) yrast-band transition, assumed to be of pure E2 character. Fig. 3 shows an example of an electron

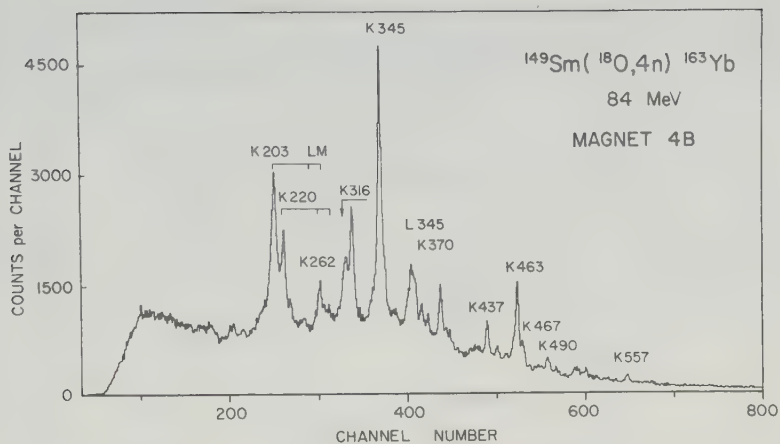


Fig. 3. Single conversion-electron spectrum induced by 84 MeV ^{18}O ions on ^{149}Sm .

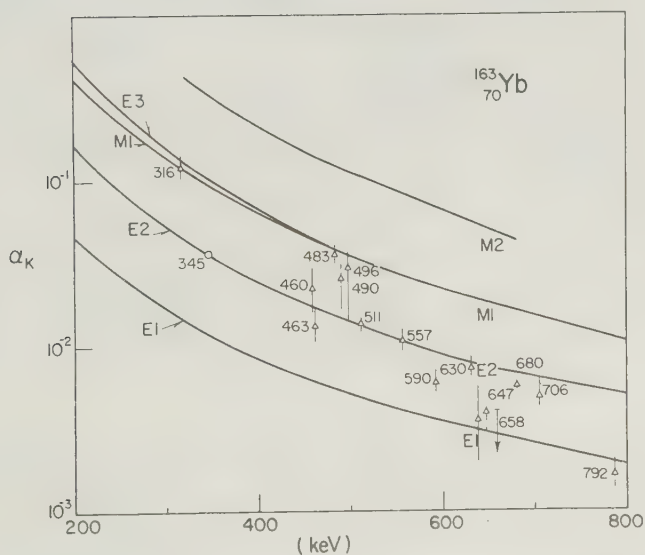


Fig. 4. Experimental and theoretical K-shell internal-conversion coefficients for the transitions belonging to ^{163}Yb .

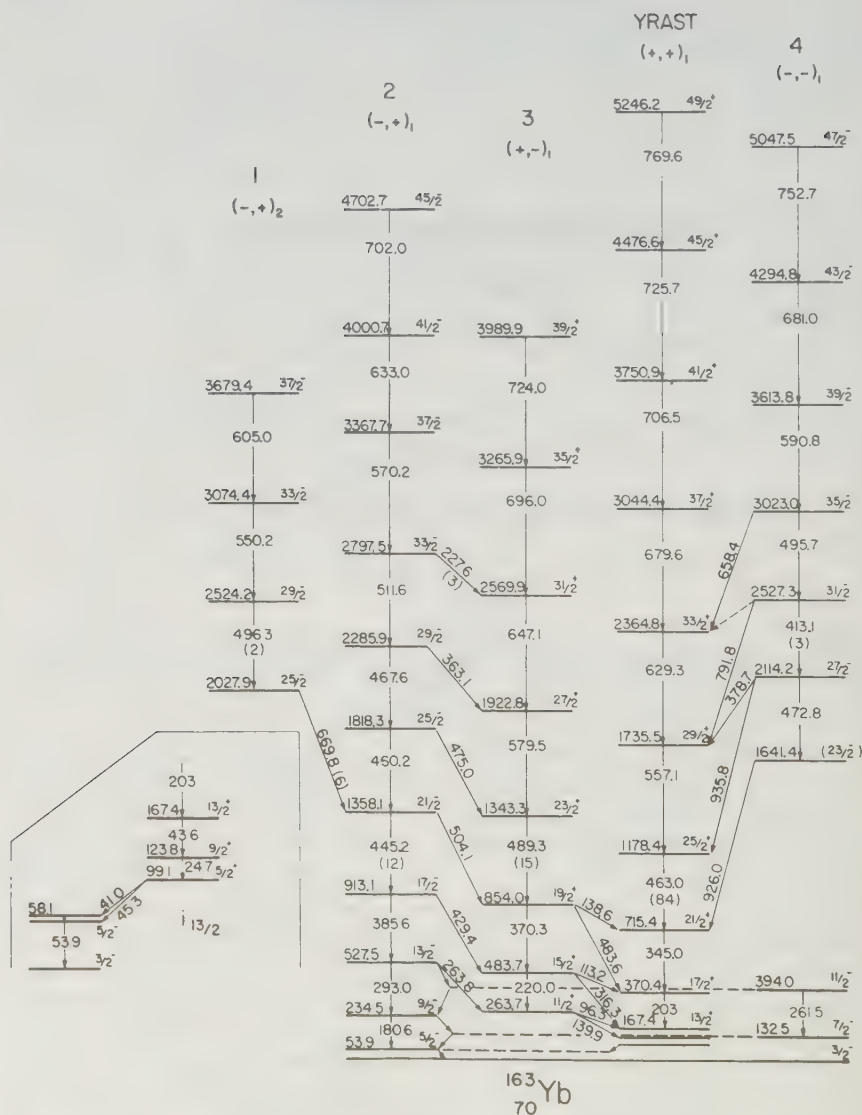


Fig. 5. Partial level scheme of ^{163}Yb . Band structures are based on coincidence data. The energies are determined within 0.3 keV. The intensity is normalized to the $1/2^+ \rightarrow 1/2^+$, 203.0 keV transition, assumed to have 100 units, and shown (numbers in brackets) only in four places of the level scheme indicating the relative population of the different bands. The bands are labelled as $(\pi, \alpha)_n$ [see also ref. ¹²] by the conserved quantum numbers of the corresponding intrinsic configurations, parity π , and signature α , (+, or - corresponds to $\alpha = +\frac{1}{2}$ or $\alpha = -\frac{1}{2}$). The $n = 1, 2, \dots$ expresses the lowest, the second lowest ... quasiparticle orbits with a given (π, α) , respectively. A superscript S can also be added $(\pi, \alpha)_n^S$ to multi-quasiparticle states to express the seniority of the configuration.

spectrum obtained during the bombardment of a 0.66 mg/cm^2 ^{149}Sm target with 84 MeV ^{18}O ions. Values of the conversion coefficients α_K are given in table 1 and compared with theoretical coefficients¹⁵⁾ in fig. 4.

3. Experimental results. Level scheme construction

Besides the yrast cascade, four additional decay sequences have been established. A level scheme of ^{163}Yb is shown in fig. 5. Table 1 lists the γ -ray energies, intensities, conversion coefficients, angular distribution results, dipole/quadrupole mixing ratios and assignments of the transitions observed in the $^{149}\text{Sm}(^{18}\text{O}, 4n)$ reaction.

3.1. THE YRAST BAND $(+, +)_1$ AND THE LOW ENERGY REGION

Members of the ^{163}Yb yrast band up to a level with spin-parity assignment $\frac{45}{2}^+$ were previously known⁷⁾. All eight transitions (203, 345, 463, 557, 629, 679, 706 and 725 keV) assigned in ref.⁷⁾ to the yrast band were also very clearly seen in the present coincidence spectra (fig. 1). The measured angular distribution and α_K conversion coefficients are compatible with the values expected for highly aligned stretched E2 transitions (table 1).

In the present experiment an additional 769.6 keV stretched E2 transition is introduced extending the yrast cascade to the $\frac{49}{2}^+$ level. An indication of the next transition ($\frac{53}{2}^+ \rightarrow \frac{49}{2}^+$) with an energy $\approx 835 \text{ keV}$ is also noted in the coincidence data.

The 43.0 keV, $\frac{13}{2}^+ \rightarrow \frac{9}{2}^+$, transition observed by Richter⁷⁾ as well as its lifetime (2.7 ns) were also confirmed in the present low-energy coincidence experiment. This experiment indicates (fig. 2a) that the $\frac{9}{2}^+$ level deexcites via 41.0, 45.3, and 53.9 keV transitions. From the lifetime measurements (fig. 2b) of the 41.0 and 45.3 keV γ -lines, the half-life of about 10 ns is established. The prompt part of the time distributions of both these lines suggests a side feeding below the isomer state.

Thus, an unobserved 24.7 keV transition should deexcite the $\frac{9}{2}^+$ level and the observed lifetime is consistent with either M1 or E2 character of this transition assuming an intrinsic quadrupole moment $Q_0^2 \approx 50 e^2 \cdot b^2$. This would be in agreement with the measured lifetime of the $\frac{13}{2}^+$ 167.9 keV state and a value of $g_K - g_R$ in accordance with the value observed for the $\frac{5}{2}^+$ [642] orbit in ^{161}Dy [ref.¹⁶⁾]. It is possible also to restrict the spin-parity assignment of the 99.1 keV level to $\frac{5}{2}^+$ and the 24.7 keV transition to be of E2 character, since a spin of $\frac{7}{2}^+$ would imply that the 263.7 keV $\frac{11}{2}^+$ state would decay to it via a 164.6 keV transition. The strength expected for the 164.6 keV transition can be judged from the observed strength and a mixing ratio δ of the $\frac{11}{2}^+ \rightarrow \frac{9}{2}^+$, 139.9 keV transition, to be a factor of 3–5 higher than the upper limit established from the data.

Thus, having a $\frac{5}{2}^+$ spin-parity assignment for the 99.1 keV level, and accepting

$\frac{5}{2}^-$ assignment for the 53.9 keV level (the present angular distribution result for the 53.9 keV γ -ray agrees with Richter's ⁷⁾ conclusion), the 45.3 keV transition is of E1 character.

However, the 58.1 keV level proposed ¹⁷⁾ from the radioactive decay of ^{163}Lu (fed here by the 41.0 keV transition), remains without spin-parity assignment. Making a lifetime estimation for the decay of the 99.1 keV ($\frac{5}{2}^+$) level, $\frac{3}{2}$, $\frac{5}{2}$ or $\frac{7}{2}$ spin and negative parity is suggested for the 58.1 keV level. Otherwise the lifetime of about 30–250 ns can be expected for the 99.1 keV level. Thus the 41 keV transition is probably of E1 character.

3.2. THE UNFAVOURABLE PORTION OF THE $i_{13/2}$ BAND WITH $(+, -)_1$

In the work of Richter ⁷⁾ another sequence of quadrupole transitions (218, 371, 490 and 579 keV) was proposed up to a level with spin-parity $\frac{27}{2}^+$. Three transitions (220, 388 and 532 keV) connecting it to the yrast band were also proposed, and this sequence was interpreted as the unfavoured portion of the $i_{13/2}$ band. In the present study this band was extended up to a spin-parity of $\frac{39}{2}^+$. The ordering of the transitions is based on coincidence intensity relationships and the identification of six interband M1/E2 transitions (96.3, 139.9, 113.3, 316.3, 138.6 and 483.6 keV) connecting this sequence with the yrast band and replacing the ones proposed in ref. ⁷⁾. We have replaced 218 keV ($\frac{15}{2}^+ \rightarrow \frac{11}{2}^+$) by the proposed intraband transition of 220 keV. In our coincidence data, 388 keV is hardly observed in the relevant gates, and 532 keV is only clearly seen in the 579 keV gate, which can be explained by the close lying 577 keV transition in ^{164}Yb . The measured K-electron conversion coefficient for the 316.3 and 483.6 keV lines indicates that these transitions are predominantly M1 (table 1), thus requiring positive parity for this band. The angular distribution coefficients for the 96.3, 113.3, 139.9 and also 316.3 and 483.6 keV lines are consistent with those expected for M1/E2 transitions.

3.3. BAND 2 $(-, +)_1$ AND BAND 1 $(-, +)_2$

The 53.9 keV line assigned as the $\frac{5}{2}^- \rightarrow \frac{3}{2}^-$ transition is observed in coincidences with the stretched E2 cascade consisting of ten γ -rays also observed in ref. ⁷⁾. However, a changed order and slightly different energies of three transitions are found in the present experiment. This band, as extended up to the $\frac{45}{2}^-$ level, displays a smooth upbend instead of a sharp backbend as reported earlier ⁷⁾. It is labeled in fig. 5 as band 2 $(-, +)_1$.

A second $(-, +)$ decay sequence consisting of three stretched E2 transitions has been proposed up to spin-parity $\frac{37}{2}^-$ and is labeled as band 1 $(-, +)_2$. The parity assignment of this band is solely based on the quadrupole character of the 669.8 keV transition connecting this band with band 2 $(-, +)_1$.

3.4. BAND 4 $(-, -)_1$

Band 4 is connected to the yrast band by five transitions with energies 658.2 ($\frac{35}{2}^- \rightarrow \frac{33}{2}^+$), 791.8 ($\frac{31}{2}^- \rightarrow \frac{29}{2}^+$), 378.7 ($\frac{27}{2}^- \rightarrow \frac{25}{2}^+$), 935.8 ($\frac{27}{2}^- \rightarrow \frac{25}{2}^+$) and 926.0 keV ($\frac{23}{2}^- \rightarrow \frac{21}{2}^+$). The measured internal conversion coefficients for the 658.2 and 791.8 keV lines are close to those calculated for E1 transitions (fig. 4), and the angular distribution coefficients for all five transitions are consistent with the expected values for $\Delta I = 1$ dipole transitions. Consequently negative parity has been assigned to this band. The intraband transitions have angular distribution coefficients consistent with those expected for stretched quadrupole transitions. The excitation energy and the intensity of population of this decay sequence are consistent with that expected for the extension of the unfavoured portion of the ground-state band above the band crossing. Therefore, in the decay scheme this sequence is placed above the ground-state band and is labeled $(-, -)_1$. Connections (i.e. the 227.6, 363.1, 475.0, 504.1, 429.4 and 263.8 keV transitions) between the unfavoured $(+, -)_1$ band and the negative-parity band $(-, +)_1$ have been identified, establishing the absolute excitation energies of the yrast $(+, +)_1$ as well as the $(+, -)_1$ and $(-, -)_1$ decay sequences.

Richter⁷⁾, using the $^{152}\text{Sm}(^{16}\text{O}, 5n)$ reaction, has proposed a cascade of stretched E2 transitions (198, 318, 425, 519, 597 and 667 keV) in ^{163}Yb with intensities below 10% of that of the 203 keV transition. In the $^{149}\text{Sm}(^{18}\text{O}, 4n)$ reaction at $E = 84$ MeV, the intensity of this cascade is only $\approx 2\%$ of that of the 203 keV transition. In order to understand this discrepancy, cross bombardment data were obtained for the following reactions:

$$\begin{aligned} ^{153}\text{Eu}(^{14}\text{N}, xn), & \quad 68 \text{ MeV} \leq E \leq 75 \text{ MeV}, \\ ^{152}\text{Sm}(^{14}\text{N}, xn), & \quad 64 \text{ MeV} \leq E \leq 68 \text{ MeV}, \\ ^{154}\text{Sm}(^{14}\text{N}, xn), & \quad 64 \text{ MeV} \leq E \leq 75 \text{ MeV}. \end{aligned}$$

In all these studies the cascade (198, ..., 667 keV) was not observed. In the reaction $^{150}\text{Sm}(^{18}\text{O}, 4n)^{164}\text{Yb}$ ($E = 83$ MeV) this cascade is also observed⁴⁾ with about the same relative intensity as in the experiment by Richter⁷⁾ but its connection to other bands in ^{164}Yb has not yet been established. We, however, are quite confident that this decay sequence is not associated with ^{163}Yb .

4. Discussion

4.1. BAND-CROSSING AND SIGNATURE-SPLITTING SYSTEMATICS IN Yb NUCLEI

It is convenient^{9, 18)} to convert the level scheme information (i.e. excitation energies as a function of I) to intrinsic frame excitation energies (routhians or e') as a function of rotational frequency, $\hbar\omega$, (see fig. 6). The detailed prescription for

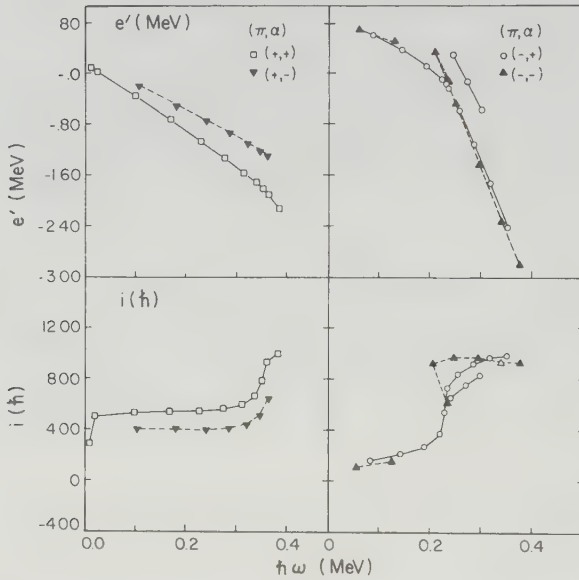


Fig. 6. Experimental energies in rotating frame (e') and aligned angular momentum (i) versus $\hbar\omega$. The dashed lines mark the negative signature bands. The negative-parity bands are on the right and the positive-parity bands on the left side of the figure.

the conversion to the rotating frame and for choosing the reference excitation energy and angular momentum projection is given in the literature [see e.g. ref. ⁹]. In the present work we have chosen to refer the data to a Harris parametrization¹⁹ of the ground-state configuration for the neighbouring even-even nuclei with moment of inertia given by

$$\mathcal{J} = \mathcal{J}_0 + \mathcal{J}_1 \omega^2, \quad (2)$$

with $\mathcal{J}_0 = 23\hbar^2 \cdot \text{MeV}^{-1}$ and $\mathcal{J}_1 = 90\hbar^4 \cdot \text{MeV}^{-3}$. When the experimental data are compared to cranked shell-model calculations in subsect. 4.2, it is referred to the yrast line of the neighbouring even-even system as described in ref. ⁵).

Nonrotational features, interpreted as crossings between rotational bands based on one- and three-quasineutron configurations, are apparent from the variation of e' (and the alignment, $i \equiv -de'/d\omega$) as a function of $\hbar\omega$ for a specific cascade (see fig. 6). The crossing frequencies, $\hbar\omega_c$, can be compared with those observed in the neighbouring even- N [refs. ^{1, 3, 4, 6, 12, 20}] and odd- N [refs. ^{2, 5, 12}] Yb isotopes (see figs. 7 and 8). The band crossing in the yrast sequence of ^{163}Yb is about 0.08 MeV higher than the crossing in the yrast sequence of ^{162}Yb and ^{164}Yb . Such a systematic

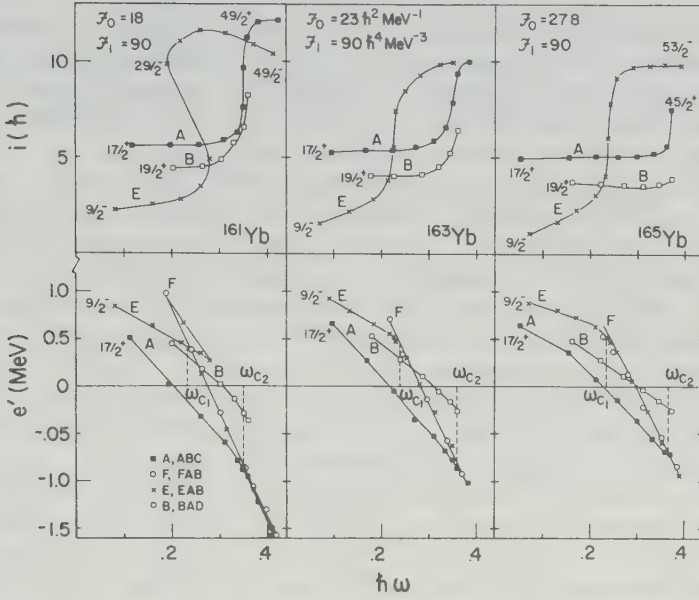


Fig. 7. Spin alignments and routhians of A(+, +)₁, B(+, -)₁, E(-, +)₁ and F(-, -)₁ bands in ¹⁶¹Yb, ¹⁶³Yb and ¹⁶⁵Yb nuclei. The reference parametrization used represents a compromise between values necessary to produce constant alignment in the ground-state band and in the S-band.

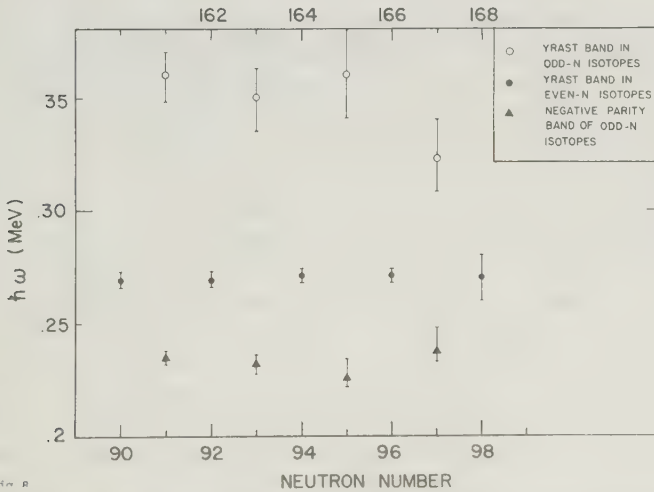


Fig. 8. Systematics of $\hbar\omega_c$ for ground-state and yrast decay sequences in even-*N* and odd-*N* nuclei.

shift of $\hbar\omega_c$ between the yrast sequences in odd- and even- N isotopes is known for a large number of rare earth nuclei (see fig. 8). In the yrast sequence of the odd- N isotope, one of the pair of $i_{\frac{1}{2}^+}$ quasineutrons which aligns at $\hbar\omega \approx 0.27$ MeV in the even- N isotope is occupied. Therefore, the Pauli principle forbids this low-frequency band-crossing in the yrast-sequence of the odd- N isotope²¹).

In contrast, in the negative-parity band of the odd- N isotope, neither of the $i_{\frac{1}{2}^+}$ quasi-neutrons, whose alignment is responsible for the band crossing in the even- N isotopes, is occupied. The band crossings in the negative-parity bands of the odd- N isotopes, should therefore corresponds to the alignment of the same pair of $i_{\frac{1}{2}^+}$ quasi-neutrons that is responsible for the band crossings in the yrast sequence of the even- N isotopes. Such band-crossing frequencies in the odd- N isotopes, however, are observed²²) to be systematically reduced by about 40 keV (see e.g. fig. 8). Even though the occupation of the negative-parity quasi-neutron configuration does not "block" the alignment of the pair of $i_{\frac{1}{2}^+}$ neutrons, it does reduce the pairing correlations. Therefore, the pairing energy is overcome at a lower $\hbar\omega$ ²²).

A significant energy splitting is observed between the different signatures of the lowest positive-parity configuration in ^{163}Yb (see fig. 6). Such splitting, which is a measure of the $\Omega = \frac{1}{2}$ component in the wave function (see subsect. 4.2), is observed to decrease with increasing N between ^{161}Yb and ^{165}Yb (see figs. 7 and 9). These systematic features are due to the shift of the Fermi surface away from the $\frac{1}{2}^+[660]$ Nilsson orbit with an increasing N (see fig. 10). At $\hbar\omega = 0.2$ MeV the splitting for ^{167}Yb is slightly larger than for ^{165}Yb , the result of the change from Fermi alignment

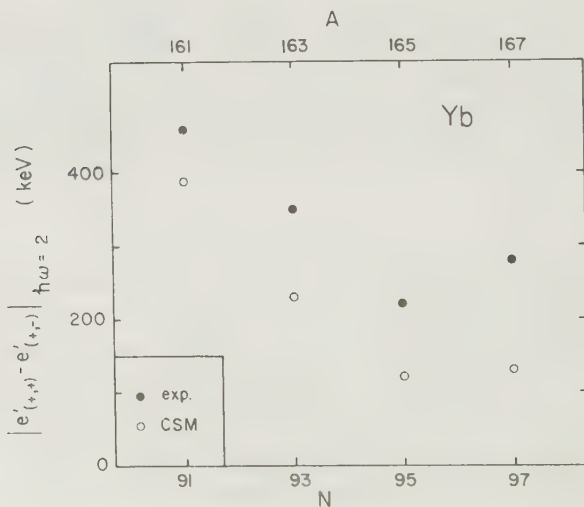


Fig. 9. Experimental and calculated (CSM) signature splitting of the yrast bands in odd- A Yb nuclei at $\hbar\omega = 0.2$ MeV.

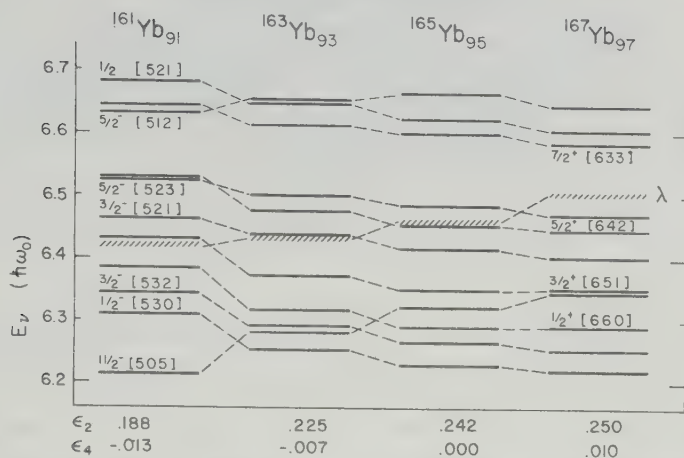


Fig. 10. Nilsson states near Fermi surface for $^{161}, ^{163}, ^{165}, ^{167}\text{Yb}$. The deformation parameters shown at the bottom are taken from ref. ²⁴).

to rotational alignment ²³) near this frequency [see ref. ⁵)]. The signature splitting in the negative-parity bands based at low $\hbar\omega$ on the $\frac{3}{2}^- [521]$ orbit is observed to be small in ^{163}Yb as well as for ^{161}Yb and ^{165}Yb [refs. ^{2, 5})].

4.2. COMPARISON WITH CRANKED SHELL-MODEL CALCULATIONS

The experimental routhians are compared in fig. 11 with the calculated intrinsic-frame excitation energies of quasineutrons moving in a rotating deformed potential (i.e. the cranked shell model⁹). Deformations ($\epsilon_2 = 0.225$ and $\epsilon_4 = -0.007$) corresponding ²⁴) to the minimum in the potential energy for $I = 0$ (which in this mass region systematically reproduces the observed deformations) and a pairing-correlation parameter ($A_n = 1.045$ MeV) which reproduces the crossing frequency in the negative-parity ground-state decay sequence ²²) were used in the calculations. These parameters, as well as the Nilsson model parameters [also taken from systematics ²⁵)], were taken to be rotational frequency and configuration independent. The Fermi surface was positioned to reproduce the correct neutron number.

The relative excitation energies of the various rotational configurations are reproduced in the calculations (see fig. 11). The band crossing in the yrast decay sequence, i.e. $(+, +)_1$, however, is observed about 20 keV higher (at 0.35 MeV, see fig. 7) in $\hbar\omega$ than predicted. Such a discrepancy is intermediate between that for ^{161}Yb and ^{165}Yb . In ^{161}Yb the predicted band crossing in the yrast decay sequences is in agreement with that observed ^{12, 26}), and in ^{165}Yb the experimental band crossing is ≈ 50 keV higher than predicted ^{5, 26}).

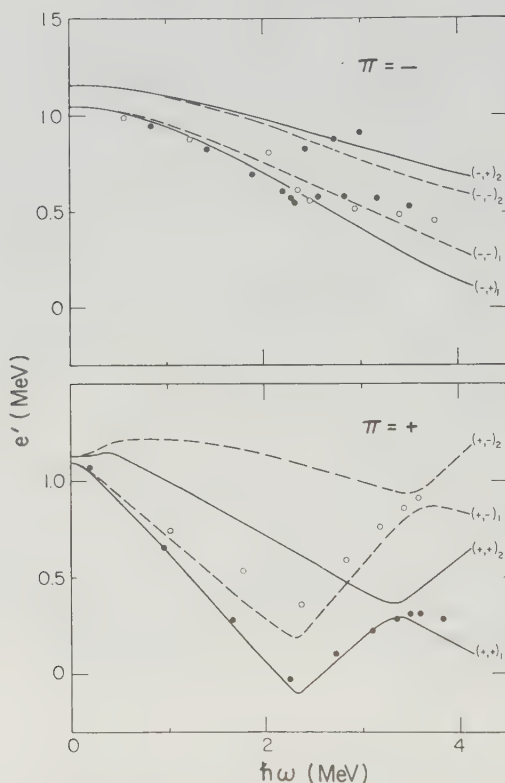


Fig. 11. Theoretical and experimental routhians for ^{163}Yb as a function of $\hbar\omega$ referred to the yrast reference. The open and filled circles denote experimental routhians with $\alpha = -\frac{1}{2}$ and $\frac{1}{2}$, respectively. Similarly dashed and solid lines correspond to CSM calculations for $\alpha = -\frac{1}{2}$ and $\frac{1}{2}$.

The change in alignment (i.e. the change of slope of e' versus $\hbar\omega$) of the negative-parity configurations at the crossing frequency results from the larger alignment gain for the $i_{1/2}$ neutron pair at the band crossing in the even-even yrast reference than in ^{163}Yb [see refs. ^{5,12}]. [A routhian corresponding to the average of the yrast bands of ^{162}Yb and ^{164}Yb is subtracted from the ^{163}Yb data in the conversion to the yrast reference^{5,12}]. Such a reduced alignment of the $i_{1/2}$ neutron pair results from reduced pairing in the odd- N isotope, a consequence of the blocking of pairing contributions from the additional pair of $i_{1/2}$ quasineutrons. Similar pairing reductions are observed for a large number of odd- N isotopes²⁶). In order to reproduce with the cranked shell model the reduced alignment of the pair of $i_{1/2}$ neutrons in the presence of the additional negative-parity quasineutron, it is necessary to reduce the pairing-correlation parameter to about 0.65 MeV. The experimental estimates of Δ_n for the various seniorities are summarized in table 2.

TABLE 2

The experimental estimates for Δ_n for the various seniorities

Seniority	Δ_n (MeV)	Reference
0	1.270	average of $^{162,164}\text{Yb}$, ref. ²²⁾
1	1.045	from $\hbar\omega_c$ in g.s. band of ^{163}Yb
3	0.65	alignment of $(-, +)_1$ band after band crossing

The routhian of the $(-, +)_2$ configuration which is only defined at large $\hbar\omega$ also deviates from the calculation (see fig. 11); however, the relative alignment of the $(-, +)_2$ configuration and the other configurations, e.g. the $(-, +)_1$ and $(-, -)_1$ at the same $\hbar\omega$ is meaningful. Therefore this configuration is not as aligned as the $(-, +)_1$ and $(-, -)_1$ configurations in agreement with the cranked shell-model predictions. It also is noted that the $\frac{25}{2}^-$ state of the $(-, +)_2$ configuration decays to the $\frac{21}{2}^-$ state of the $(-, +)_1$ band, by a 670 keV E2 transition in preference to an unobserved, possible 685 keV E1 transition to the $\frac{23}{2}^+$ state of the $(+, -)_1$ configuration (see fig. 5). The $(-, +)_1$ and $(-, +)_2$ configurations are derived from pseudospin partners ²⁷⁾. The upper limit of the 685 keV transition is a factor of 4–5 times less than the observed intensity of the 670 keV transition (see fig. 1). Therefore, either the 670 keV E2 transition is enhanced or the E1 transition between the $(-, +)_2$ and $(+, -)_1$ configurations is hindered with respect to the E1 transitions between the $(-, +)_1$ and $(+, -)_1$ configurations. Such a hindrance of the E1 transition may be the result of the higher K value of the $(-, +)_2$ configuration than for the $(-, +)_1$ configuration. We also note that the 58.1 keV level (see sect. 3.1), which must have negative parity and is probably $I^\pi = \frac{3}{2}^-, \frac{5}{2}^-, \text{ or } \frac{7}{2}^-$, must be associated with the low-spin portion of the $(-, +)_2$ or $(-, -)_2$ configurations. The most likely candidate is the $\frac{5}{2}^-$ band head of the $(-, +)_2$ band. Therefore, the $(-, +)_1$ and $(-, +)_2$ bands are closer in energy at low spin than at high spin in agreement with the smaller predicted alignment for the $(-, +)_2$ configuration (see fig. 11).

For axially symmetric systems which also are unchanged by a rotation of 180° about an axis perpendicular to the axial symmetry axis, a signature-dependent decoupling is observed [†] in the energies for rotational sequences based on $K = \frac{1}{2}$ intrinsic configurations ⁸⁾.

$$E = E_{\text{int}} + \frac{\hbar^2}{2\mathcal{J}} \left[I(I+1) + a(-1)^{I+\frac{1}{2}} (I+\frac{1}{2}) \delta(K, \frac{1}{2}) \right]. \quad (3)$$

[†] The signature-dependent term is derived from Coriolis and centrifugal forces acting on the nucleon in a rotating system which connect states differing by one unit in K . For $K = \frac{1}{2}$ bands such a force can connect the $K = +\frac{1}{2}$ and $-\frac{1}{2}$ components which are present in the wave function. The signature-dependent term has an alternative sign for $\alpha = +\frac{1}{2}$ and $-\frac{1}{2}$ bands ($I = \alpha \bmod 2$).

Here E_{int} is the excitation energy associated with the intrinsic degrees of freedom, $\mathcal{J}$ is the moment of inertia for rotation about an axis perpendicular to the symmetry axis, and K is the projection of the total angular momentum, I , on the symmetry axis. The decoupling parameter, a , is given by

$$a = \sum_j (-1)^{j-\frac{1}{2}} (j + \frac{1}{2}) |c_{j\Omega=\frac{1}{2}}|^2, \quad (4)$$

where j is the angular momentum of the unpaired nucleon and $c_{j\Omega=\frac{1}{2}}$ is the Nilsson coefficient expressing the intrinsic configurations in terms of a spherical (shell-model) basis. Under rotation K is no longer a constant of the motion; therefore, the $\Omega = K = \frac{1}{2}$ component is mixed into the other configuration producing a decoupling or signature-dependent splitting. This signature splitting is a probe of the wave function for the $\Omega = \frac{1}{2}$ component of the intrinsic configuration. For a positive decoupling constant, corresponding to an intrinsic configuration dominated by $j = \frac{1}{2}, \frac{5}{2}, \frac{9}{2}, \frac{13}{2}, \dots$, the excitation energy of the $\alpha = \frac{1}{2}$ band is lowered relative to the $\alpha = -\frac{1}{2}$ band. (Similarly for $a < 0$ the energy of the $\alpha = -\frac{1}{2}$ configuration is lowered.) Therefore, for shells with an even number of oscillator quanta, (i.e. N even), a favouring of the $\alpha = \frac{1}{2}$ configuration corresponds to a domination of $j = l + \frac{1}{2}$ in the $\Omega = \frac{1}{2}$ component of the wave function.

For the positive-parity decay sequences a positive signature-splitting or decoupling is observed (i.e. the excitation energy of the $\alpha = \frac{1}{2}$ decay sequences is reduced relative to the $\alpha = -\frac{1}{2}$ decay sequence). Such a splitting is expected, and indeed is predicted (see fig. 11), for states dominated by $i_{\frac{13}{2}}$ neutron configurations. The magnitude of the signature-splitting for the positive-parity configuration, however, is predicted systematically to be smaller than observed [see figs. 9 and 11 and refs. ^{12, 26}].

For the lowest negative-parity bands a small positive splitting is observed at low $\hbar\omega$ (i.e. band 2 $(-, +)_1$ is lowered in energy relative to band 4 $(-, -)_1$). At larger $\hbar\omega$ a small negative decoupling is observed (band 4 lies lower in energy than band 2). For both neighbouring odd- N Yb isotopes, ^{161}Yb and ^{165}Yb , a small positive splitting is observed at large values of $\hbar\omega$ for the lowest negative-parity configuration $2^-, 5^-, 12^-, 26^-$ (both signatures only known above the backbend). Cranked shell-model calculations predict a positive decoupling for all the light Yb isotopes that is quite large for ^{161}Yb with a decrease in magnitude with increasing neutron number ^{12, 26}). The $\frac{1}{2}^-$ [530] Nilsson orbit, which is predicted to be the nearest $\Omega^\pi = \frac{1}{2}^-$ orbit to the Fermi surface for $^{161}\text{Yb}_{91}$ and $^{163}\text{Yb}_{93}$ (see fig. 10), is known to have a small positive decoupling for the low-spin states ^{28, 29}) in $^{155}\text{Gd}_{91}$ in agreement with that observed for $^{161}\text{Yb}_{91}$ and the low-spin domain of $^{163}\text{Yb}_{93}$. The large splitting predicted in the cranked shell-model for the $\frac{3}{2}^-$ [521] band has been attributed ^{12, 26}) to an incorrectly predicted wave function for the $\frac{1}{2}^-$ [530] Nilsson configuration which has a large matrix element with the states of the $\frac{3}{2}^-$ [521] configuration.

Indeed this discrepancy can be remedied by a relatively small change in the Nilsson model parameters, κ and μ . Such a parameter change also can produce the observed negative splitting at higher spins for the $(-, +)_1$ and $(-, -)_1$ configurations of ^{163}Yb if a reduced value of Δ is used for these seniority-three states. [Using e.g. the κ - and μ -values from Chi³⁰⁾ which give the negative decoupling, however, introduces discrepancies in the ordering of the Nilsson states near the Fermi surface]. Therefore, the change in the sign of the decoupling between ^{161}Yb and ^{163}Yb is probably a result of the increase in deformation with an increase in neutron number²⁴⁾. The decoupling parameter of the $\frac{1}{2}^- [530]$ orbit is predicted³⁰⁾ to decrease with increasing ε_2 becoming negative at $\varepsilon_2 \approx 0.24$ about the value predicted²⁴⁾. ($\varepsilon_2 \approx 0.225$) for ^{163}Yb . Similarly the change in the sign of the decoupling between low- and high-spin portions of the $(-, +)_1$ and $(-, -)_1$ configurations of ^{163}Yb also may be the result of a relatively small change in deformation for these configurations before and after the alignment of the pair of $i_{1/2}$ neutrons. Such effects are known in other nuclei in this mass region³¹⁾. The $\frac{1}{2}^- [521]$ orbit, which is the $\Omega^\pi = \frac{1}{2}^-$ orbit nearest the Fermi surface for ^{165}Yb and ^{167}Yb , is expected to have a positive decoupling for all deformations³⁰⁾. This expectation is confirmed by experiment³²⁾.

Even though it would be possible to understand the negative signature splitting observed at large $\hbar\omega$ for the lowest negative-parity states of ^{163}Yb in terms of shell-model components in the wave function and to produce such a splitting in cranked shell-model calculations by a small adjustment of the Nilsson parameters κ and μ , there are theoretical arguments based on the pseudospin formalism for rotating systems²⁷⁾ indicating that the signature of the lowest yrast quasiparticle state should be

$$\alpha = \frac{1}{2}(-1)^{\tilde{N}}, \quad (5)$$

where $\tilde{N}$, the pseudospin oscillator quantum number²⁷⁾ is equal to 4 for states derived from the $1h_{3/2}$, $2f_{7/2}$, $2f_{5/2}$, $3p_{3/2}$, and $3p_{1/2}$ shell-model configurations. Therefore, throughout this mass region an $\alpha = \frac{1}{2}$ band would be expected to be the lowest negative-parity configuration. In the $N = 91$ – 101 mass region this rule is only violated for ^{163}Yb [see figs. 10 and 11 of ref. ²⁶⁾].

4.3. ROTATIONAL EFFECTS ON M1 TRANSITIONS

Recently, there has been a revival of theoretical interest^{10, 33, 34)} in the topic of strong perturbation effects of rotation on the electromagnetic (M1 and E2) transition matrix-elements within a band with a fixed intrinsic structure. Namely, the M1 transitions between states of the two different signatures of the positive-parity band observed in ^{163}Yb and in a number of other nuclei are of particular interest. In a similar way, as discussed in sect. 4.2 for the role of the decoupling parameter on the signature dependence of excitation energies through the amplitude of $\Omega = \frac{1}{2}$ in the wave function, there is a signature dependence in the magnetic (M1)

decay [ref. ⁸)] properties, which is ruled by the magnetic decoupling parameter b .

$$B(M1; KI_1 \rightarrow KI_2 = I_1 \pm 1) = \frac{3}{4\pi} \left(\frac{e\hbar}{2Mc} \right)^2 (g_K - g_R)^2 K^2 | \langle I_1 K 10 | I_2 K \rangle |^2 \\ \times [1 + (-1)^{I_>} + \frac{1}{2} b \delta(K, \frac{1}{2})]^2, \quad (6)$$

where $I_> = \max(I_1, I_2)$ and the magnetic decoupling parameter, b , is given by

$$(g_K - g_R)b = -(g_I - g_R)a - \frac{1}{2}(-1)^I(g_s + g_K - 2g_I). \quad (7)$$

Therefore, when the magnetic decoupling is expected to be large, e.g. for the $(+, +)_1$ and $(+, -)_1$ configurations in ^{163}Yb where a large signature dependence is observed in the routhians, it is not appropriate to parameterize the M1 transition rates solely in terms of $g_K - g_R$. Such a parameterization disregards the second term in eq. 6. When a strongly decoupled $\Omega = \frac{1}{2}$ configuration is near the Fermi surface, large signature-dependent effects are expected for allowed M1 transition rates between intrinsic configurations based on signature partners, e.g. between the states of the $(+, +)_1$ and $(+, -)_1$ configurations.

The relative M1 transition rates for ^{163}Yb obtained from experimental branching- and mixing ratios are compared in table 3 with calculations from the cranking model³³). Parameters identical to those used to calculate the energy levels shown in fig. 11 (see sect. 4.2) were used. The experimental

TABLE 3

Measured M1 transitions in ^{163}Yb , obtained from (HI, xn) reactions, which show a strong rotational perturbation

$I_{\text{in.}}$ ($\alpha = -\frac{1}{2}$)	$I_{\text{fin.}}$ ($\alpha = +\frac{1}{2}$)	Transition energy (keV)	I_γ intensity	$B(M1)_B/B(M1)_A$		$\frac{B(M1)_B^a)}{B(M1)_A}$	$\hbar\omega_{\text{rot}}$ (in $\hbar\omega_0$)
				exp. ^{b)}	theor.		
$\frac{11}{2}^+$	$\frac{8}{2}$	$\frac{13}{2}^+$	96.3	1.0	6.4	25.7	1.15
$\frac{11}{2}^+$	$\frac{4}{2}$	$\frac{9}{2}^+$	139.9	1.0			0.015
$\frac{13}{2}^+$	$\frac{8}{2}$	$\frac{17}{2}^+$	113.3	2.5	15.9	22.2	1.13
$\frac{13}{2}^+$	$\frac{4}{2}$	$\frac{13}{2}^+$	316.3	3.9			0.020
$\frac{19}{2}^+$	$\frac{8}{2}$	$\frac{21}{2}^+$	138.6	1.0	17.3*	19.3	1.11
$\frac{19}{2}^+$	$\frac{4}{2}$	$\frac{17}{2}^+$	483.7	3.0			0.028
$\frac{23}{2}^+$	$\frac{8}{2}$	$\frac{25}{2}^+$	164.9	<0.1		17.5	1.09
$\frac{23}{2}^+$	$\frac{4}{2}$	$\frac{21}{2}^+$	627.9	<0.2			0.036

^{a)} In this column the ratio of CG coefficients $(I, K 10, I, K)^2$ is given as equal to the ratios of $B(M1)$ values in the absence of rotational perturbation.

^{b)} Corrected for E2 admixture.

* Value obtained when calculating $\delta(E2/M1)$ from measured branching ratio

$$\lambda = \frac{I_{370}(\frac{19}{2}^+ \rightarrow \frac{15}{2}^+)}{I_{138}(\frac{19}{2}^+ \rightarrow \frac{21}{2}^+)}.$$

observation of rotationally enhanced $I+1, \alpha = \frac{1}{2} \rightarrow I, \alpha = -\frac{1}{2}$ M1 transition rates (type B) relative to $I+1, \alpha = -\frac{1}{2} \rightarrow I, \alpha = \frac{1}{2}$ (type A) is reproduced by the calculation.

Although no absolute transition rates have been measured, some information on the M1 matrix elements can be extracted by a comparison to the E2 strength. From the experimental branching ratios $\lambda = I_\gamma(I \rightarrow I-2)/I_\gamma(I \rightarrow I-1)$ or the mixing ratios δ for $I \rightarrow I-1$ transitions it is possible to determine the ratio $B(M1)/Q_0^2$. Such an analysis is independent of the value of the magnetic decoupling parameter [see the equations relating $B(M1)/Q_0$ to λ and δ in ref. 5)]. For an analysis in terms of $B(M1)/Q_0^2$, however, it is necessary to assume a value for K , which in a rotating system is not a conserved quantity. It is possible, however, to estimate values of K for the low-spin portion of the positive-parity bands in the odd- N Yb nuclei, where the band-head configuration and the lower- K components which can be mixed into the configuration under rotation are known.

The $B(M1)$ values resulting from such an analysis for the transition between the two signatures of the lowest positive-parity configuration are compared in fig. 12 with similar values for $^{161}, ^{165}, ^{167}\text{Yb}$ and with the results of a particle-rotor-model calculation¹⁰⁾ appropriate for ^{165}Yb .

The present case of ^{163}Yb extends rather high in spin and is clearly showing the expected enhancement interchanging with retardation of the $B(M1)$ values with spin

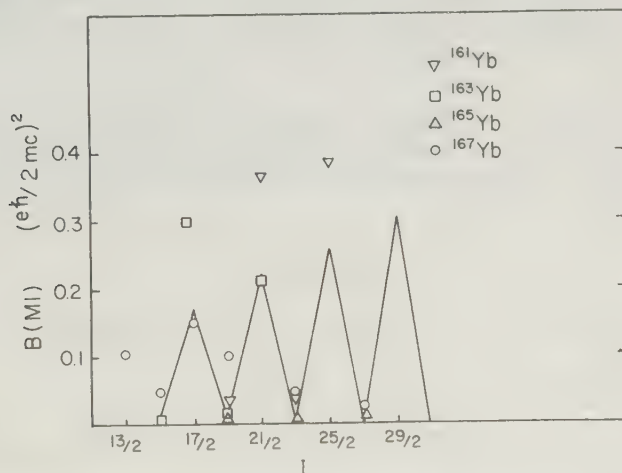


Fig. 12. $B(M1)$ values for transitions between I and $I-1$ states of opposite signature of the $i_{13/2}$ band in odd- A Yb nuclei^{2, 3, 6}). These values were derived using $Q_0^2 = 50 e^2 \cdot b^2$, a value of $K = \frac{5}{2}$ for $^{163}, ^{165}, ^{167}\text{Yb}$ and $K = \frac{3}{2}$ for ^{161}Yb . A $K = \frac{1}{2}$ admixture would slightly increase the enhanced and decrease the retarded $B(M1)$ values. The "saw-tooth" line shows the calculated¹⁰⁾ reduced transition probabilities between the neutron yrast states in a particle-rotor model. The parameters used are chosen so as to be suitable for the nucleus $^{165}\text{Yb}_{95}$.

values which are all below the backbend of these yrast positive-parity bands. Since the $\frac{1}{2}^+[660]$ is closer to the Fermi surface in ^{163}Yb than in ^{165}Yb for which the calculation is performed, a larger signature dependence is expected.

5. Summary

In the present work the $(+, +)_1$, $(+, -)_1$ and $(-, +)_1$ decay sequences have been established to $I^\pi = \frac{49}{2}^+$ (tentatively $\frac{53}{2}^+$), $\frac{39}{2}^+$ and $\frac{45}{2}^-$, respectively. Two new negative-parity sequences $(-, -)_1$ and $(-, +)_2$ were established, as was the connection between the yrast $(+, +)_1$ and the ground-state $(-, +)_1$ sequences. An additional negative-parity band proposed for ^{163}Yb by ref. 7) was, however, not assigned to ^{163}Yb in the present study. Systematics of band crossing frequencies and signature-dependent splitting in energy and M1 transition rates are summarized for odd- N Yb isotopes and are compared with model calculations. The relation between the energy and magnetic decoupling parameters, a and b , for non-rotating systems and the signature-dependent splittings in excitation energy and M1 transition rates in rotating systems is reiterated.

Probably, the most striking feature of this work is the observation at large $\hbar\omega$ of the $(-, -)_1$ configuration lower in energy than the $(-, +)_1$ configuration. This negative decoupling of energy for the negative-parity decay sequence is unique in the $N = 90$ -102 mass region ^{2, 5, 26}) and is in conflict with cranked shell-model calculation and with pseudospin selection rules ²⁷).

Discussions with Aa. Bohr, S. Frauendorf, I. Hamamoto, B. Mottelson, Z. Szymański and J. Lyttkens are acknowledged as is the financial support of the Danish Natural Science Research Council and the Nordic Committee for Accelerator Based Research.

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COSMIC AND SUBATOMIC PHYSICS REPORT
LUIP 8304
MARCH 1983
LUNFD6/(NFFK-7027)1-39(1983)
ISSN 0348-9329

NEAR-YRAST SPECTROSCOPY OF ^{164}Yb
AND NEIGHBOURING NUCLEI

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Abstract: High-spin states in ^{164}Yb have been populated in the $^{152}\text{Sm}(^{16}\text{O},4n)$ and $^{150}\text{Sm}(^{18}\text{O},4n)$ reactions. From studies of γ - γ coincidences, γ -ray angular distributions and conversion electron measurements the level scheme has been constructed. The g-band and the S-band have been established to spin and parity 22^+ and 26^+ , respectively, and the rotational sequences $(\pi,\alpha) = (-,1)_1$, $(-,0)_1$ and $(-,0)_2$ to 23^- , 24^- and 18^- , respectively. The side-bands in $^{162,164}\text{Er}$ and $^{164,166}\text{Yb}$ are discussed. Constructed two-quasineutron configurations and cranked shell model (CSM) calculations are compared with the experimental results in ^{164}Yb . Residual interactions between quasiparticles in ^{164}Yb are calculated. Crossing frequencies and the gain in alignment are summarized for the Yb isotopes and the main features are discussed.

NUCLEAR REACTIONS $^{150,152}\text{Sm}(^{18,16}\text{O},xn)$, $E=81-84$ MeV; measured γ - γ coin., $\gamma(\theta)$, ICC, following 4 neutron emission. ^{164}Yb deduced levels, J , π . Enriched targets, Ge(Li) detectors, Compton-suppressed Ge(Li) coincidence set-up, mini-orange spectrometer, Si(Li) detector.

NUCLEAR STRUCTURE ^{164}Yb ; deduced two-quasineutron routhians, alignments and two-quasineutron residual interaction. Cranked shell model comparison.

1. Introduction

Recent years have witnessed a rapid expansion in the experimental information about the band structure in well-deformed nuclei, mostly due to the improved experimental techniques. On the theoretical front, developments of the cranked shell model (CSM) ^{1,2)} have provided us with a microscopic theory for understanding these bands in terms of independent quasiparticle motion in rotating deformed potentials. Furthermore, it has given an impetus for a systematic elucidation of yrast and near-yrast bands in deformed nuclei.

The present work is one in a series of such near-yrast spectroscopic studies of light Yb nuclei ³⁻¹⁰⁾. Systematic data for not only the yrast sequences of states, but also for a number of quasineutron side-bands in ¹⁶⁰⁻¹⁶⁷Yb have now become available. This article presents new experimental information for a number of quasineutron bands in ¹⁶⁴Yb. The structure of the side-bands is explained by making a detailed comparison with the corresponding bands in ^{162,164}Er and ¹⁶⁶Yb. The systematics of the crossing frequencies and the gain in alignment in Yb isotopes are summarized and the most important features are discussed. Some preliminary data for ¹⁶⁴Yb has been presented in a report ¹¹⁾ and some of the data have been used in refs. ^{12,13)}.

2. Experimental techniques and results

High-spin states in ^{164}Yb were populated in the $^{152}\text{Sm}(^{16}\text{O},4n)$ and $^{150}\text{Sm}(^{18}\text{O},4n)$ reactions, using 81-84 MeV ^{16}O and 83 MeV ^{18}O beams, from the NBI tandem accelerator. These beam energies were near the optimum for these reactions, resulting also in an appreciable population of the side-bands to quite high spin values. The number of competing reaction channels was small. Around 80% of the compound nucleus cross-section was found in the 4n exit channel, the main contaminants being the 3n, 5n and α 3n exit channels. The experiments consisted of γ -ray angular distribution, γ - γ coincidence and conversion electron coefficient measurements. Isotopically enriched (>98%) metallic targets of ^{152}Sm and ^{150}Sm supported on ^{208}Pb backings were used for the measurements.

Gamma-gamma coincidences were measured for the $^{152}\text{Sm}(^{16}\text{O},4n)$ reaction at 84 MeV using a 2.5 mg/cm^2 ^{152}Sm target on a 4.1 mg/cm^2 lead backing. The experimental set-up consisted of five Compton-suppressed Ge(Li) detectors. The experimental procedure was similar to that given in ref. 9) and the set-up has been described elsewhere 14). About 36 million Compton-suppressed coincidence events were accumulated for off-line analysis. Typical coincidence spectra are shown in fig. 1.

Gamma-ray angular distributions were measured at 81 MeV using the same reaction and target as for the coincidence measurements. A set of singles γ -ray spectra was acquired

with a Compton-suppressed Ge(Li) detector subsequently placed at five different angles between 0° and 90° . A stationary Ge(Li) detector placed below the target served as a monitor. Efficiency calibrations at various angles were made with a ^{152}Eu source placed at the target position. The angular distribution coefficients were obtained, after dead-time corrections, by fitting the normalised peak intensities to the expression

$$\omega(\theta) = A_0 + A_2 P_2(\cos \theta) + A_4 P_4(\cos \theta).$$

The transition energies were determined by recording simultaneously at 90° the γ -rays from the reaction and the γ -rays from ^{152}Eu and ^{137}Cs sources placed near the target.

To obtain the internal conversion coefficients of the interband transitions, conversion electron spectra, gated by a NaI(Tl) multiplicity filter, were acquired at 55° with a mini-orange spectrometer and a cooled Si(Li) detector. Three different magnet configurations were used, in order to span the range of electron energies from about 300 keV to about 1200 keV. The reaction $^{150}\text{Sm}(^{18}\text{O}, 4n)$ at 83 MeV was used for this study. To reduce the straggling of the conversion electrons, a thin (0.8 mg/cm^2) target of ^{150}Sm on a thin lead backing (1 mg/cm^2) was used. The γ -spectra gated by the same multiplicity filter were recorded simultaneously at -125° . The conversion coefficients were normalised to the $\alpha_K(E2)$ values of the known ^{150}Sm 374.7 and 633.3 keV stretched E2 transitions along the yrast cascade.

The results of the experiments are summarised in table 1. These results form the basis for the construction of the level scheme of ^{164}Yb , as shown in fig. 2. The yrast sequence of levels was known ¹⁵⁾ up to the level having spin and parity 22^+ and has been extended up to the level assigned as 26^+ in the present study. The ground state band has been extended beyond the crossing with the S-band. Another band-crossing is observed at a slightly higher frequency than the S-band crossing. The measured conversion coefficients of the 696 and 707 keV transitions are used for the spin and parity assignments of levels up to 22^+ . This is made assuming that the E2 character of the 707 keV line is valid for both of the 707 keV transitions. Three negative parity bands have been established and, on the basis of spin and parity these bands are assigned to be the $(-,1)_1$, $(-,0)_1$ and $(-,0)_2$ bands ^{9)*}.

The spin and parity assignments follow the measured angular distribution and conversion coefficient results,

* The rotational configurations $(\pi, \alpha)_n^S$ are labelled by the conserved quantum numbers of the corresponding intrinsic quasiparticle configurations, parity, π and signature α (+ or - corresponds to $\alpha = +1/2$ or $\alpha = -1/2$; when $\alpha = 1$ or 0 it is explicitly stated). The subscript n designates that this configuration is the n th such configuration with these quantum numbers. A superscript S is added to multi-quasiparticle states to designate the seniority of the configuration.

except for a few contaminated intraband transitions, for which the multipolarity assignments are based on the transition energy systematics within a band. Two transitions with energies of 287 and 474 keV are found to be feeding the even-spin members of an odd-parity band based on the level at 1551.6 keV. The weakness of these transitions as well as the presence of contaminant lines prevents a firm assignment of these transitions. The low-spin intrinsic states in ^{164}Yb , known from the radioactive decay of ^{164}Lu (ref. 15), are not populated in the reactions used and are not included in the level scheme (fig. 2). On the other hand, a few new intrinsic states have been located in the present study and these are shown at the left hand side of fig. 2. Except for the case of a 5^+ state, the spins and parities of these states could not be assigned.

3. Discussion

3.1. The routhians and the choice of a reference frame

One basic approach towards an understanding of the band structure is the cranked shell model (CSM), based on the notion of a single-particle motion in a rotating deformed potential ^{1,2}). In order to compare the experimental results with the CSM prediction it is convenient to convert the level scheme information to excitation energies ϵ' in a rotating intrinsic frame (the routhians) and express them as functions of the rotational frequency

$\hbar\omega$. The detailed prescription for such a transformation is found in ref. ²⁾. It has been customary to refer the data to the energies of a parametrized ground-state band with the moment of inertia described by the Harris ¹⁶⁾ formula

$$\mathcal{I} = \mathcal{I}_0 + \omega^2 \mathcal{I}_1$$

The parameters $\mathcal{I}_0$ and $\mathcal{I}_1$ are assumed to describe the collective behaviour of the nucleus. One set of parameters can therefore not take into account changes in the collective properties caused by the alignment of various quasiparticles. Such changes in the collective properties may result from a change of the deformation. Furthermore, due to blocking effects the pairing correlation is reduced in bands based on excited quasiparticles compared to the ground-state band. The choice of parameters is therefore non-trivial ^{2,12,17,18)}. However, fitting the reference parameters to the S-band or some of the side-bands, allows us to determine an average set of parameters, relevant for a set of bands (e. g. the two-quasiparticle bands). The use of such average reference frames will result in slightly non-zero alignments ¹⁾, $i_x = -de^-/d\omega$, in the ground-state band and sometimes a slight decrease of the alignment with increasing frequency in the S-band. The values $\mathcal{I}_0 = 25.8 \text{ MeV}^{-1} \hbar^2$ and $\mathcal{I}_1 = 90 \text{ MeV}^{-3} \hbar^4$ used for ^{164}Yb represent these average numbers. The routhians for the different bands in ^{164}Yb are presented in fig. 3 and the alignments are plotted in fig. 4.

3.2. Construction of two-quasineutron configurations and residual interaction analysis

In the discussions below the following nomenclature of the quasiparticle orbitals is frequently used: $(+,+)_1=A$, $(+,-)_1=B$, $(-,+)_1=E$ and $(-,-)_1=F$.

The one-quasineutron configurations A, B and E known in ^{163}Yb [ref.¹⁰] and ^{165}Yb [ref.⁹] can be used to construct two-quasineutron configurations for the adjacent doubly-even ^{164}Yb nucleus (see fig. 5). In the construction of the two-quasineutron routhians average values of the appropriate single-quasineutron routhians in ^{163}Yb and ^{165}Yb are used. Such an averaging procedure should incorporate effects which vary smoothly with the neutron number. The constructed two-quasineutron routhians are shifted upwards by a constant term ⁹⁾ of $2\Delta_n^{\text{ce}}=2.10$ MeV. The value for this shift is chosen so that the constructed routhian from the A and B configurations will reproduce the S-band in ^{164}Yb , which is assumed to have a very pure structure. The constructed and the experimental AB bands overlap very well. The other two constructed configurations AE and BE do not fit well to the experimental values for the negative parity bands and these discrepancies will be discussed later. It should be noted that there is very limited information on the F-band in the odd-N isotopes (see fig. 5) but it can be assumed to lie very close in energy to the E band and therefore the constructed AE and AF configurations should lie very close in energy.

From the energies $e'_\mu(\omega)$ in the rotating frame of one-quasiparticle and three-quasiparticle bands in the neighbouring odd-A nuclei $^{163,165}\text{Yb}$ and the two-quasiparticle bands in ^{164}Yb composed of the same quasiparticles it is possible to extract a value of the residual interaction $V_{\mu\nu}$ between quasiparticles. In this analysis one assumes ¹⁹⁾ that the energy of a composite state can be written as

$$e^-(\omega) = \sum_{\mu} e'_\mu(\omega) + \sum_{\mu > \nu} V_{\mu\nu}(\omega) \quad (1)$$

In this expression the energy $e^-(\omega)$ is given relative to a reference value $e'_g(\omega)$ which can be chosen differently for the odd and the even systems. In order to compare the odd and even systems it also is necessary to shift the energies by the pairing gap energy Δ . A combination of one- two- and three-quasiparticle configurations yields the following equations from which both Δ and four different residual interactions $V_{\mu\nu}$'s can be obtained

$$\left. \begin{aligned} \Delta &= 1/4(e'_{AB} + e'_{AE} + e'_{BE} - e'_A - e'_B - e'_E - e'_{ABE} - 3e'_g^e + 4e'^o_g) \\ V_{AB} &= 1/2(e'_{AB} - e'_{AE} - e'_{BE} - e'_A - e'_B + e'_E + e'_{ABE} + e'_g^e) \\ V_{AE} &= 1/2(e'_{AE} - e'_{AB} - e'_{BE} - e'_A - e'_E + e'_B + e'_{ABE} + e'_g^e) \\ V_{BE} &= 1/2(e'_{BE} - e'_{AB} - e'_{AE} - e'_B - e'_E + e'_A + e'_{ABE} + e'_g^e) \\ V_{BF} &= e'_{FAB} - e'_{AF} - e'_B + e'_g^e - V_{AB} \end{aligned} \right\} \quad (2)$$

It can be seen, that in the interaction matrix elements only the reference energy, e'_g^e , used in the even system plays a role, whereas the value extracted for Δ (this value corresponds to a Δ for a one-quasiparticle state) depends on both the odd, e'^o_g , and the even reference energies.

The values extracted are given in table 2 at three rotational frequencies. Unfortunately the range in frequency at which both one- and three-quasiparticle bands exist is rather limited, since there is some interaction between the bands. It is therefore necessary to extrapolate on either side of the crossing. However, for the narrow range in frequency given here this extrapolation ought to be of minor importance for the results obtained, adding about 20% to the uncertainty.

The uncertainty caused by the choice of reference frame can be illustrated in a calculation of the sum of V_{AE} and V_{BE} at the frequency, where $e'_E = e'_{EAB}$. At this frequency $V_{AE} + V_{BE} = e'_{EAB} - e'_E - e'_{AB} + e'^e_g = -e'_{AB} + e'^e_g = \delta\hbar\omega_d \langle i \rangle$, (3) where $\delta\hbar\omega_d$ is the shift in frequency between the g -AB crossing and the E-EAB crossing and $\langle i \rangle$ is the average gain in alignment observed at the two crossings. At $\hbar\omega = 0.225$ MeV the value of $V_{AE} + V_{BE} = -0.38$ MeV is obtained from the crossing frequency change whereas the value from equations (2) is $V_{AE} + V_{BE} = -0.36$ MeV (cf. table 2).

The extracted residual interaction is very state dependent. It is small and almost frequency independent for the S-band. It is much larger and shows a clear frequency dependence for the AE band. This is because the experimental band $[(-,1)_1]$ is not the pure AE band, but is strongly mixed with the octupole-band and therefore pressed down in energy (see subsect. 3.4.4.). Also for the BE band there is a strong frequency dependence, because

the slope of the experimental band $[(-,0)_2]$ is very different from the sum of the slopes of the corresponding one-quasiparticle bands. In order to compensate for this the residual interaction becomes frequency dependent. It should, however, already here be pointed out that the interpretation of the $(-,0)_2$ band as BE is highly questionable. Except that the extracted interactions are thus influenced by the non-purity of the two-quasiparticle configurations the sizes of the matrix elements $V_{\mu\nu}$ are to a large extent due to the blocking of orbitals, which at $\hbar\omega=0$ for an average pair of quasiparticles is estimated to amount to about half of the average level distance. In the rare earth region the average level distance is about 0.3 MeV. Changes in the deformation and the Fermi level can introduce an error in the present analysis through a change in the quasiparticle vacuum. By averaging the one- and three-quasiparticle states of the odd system over ^{163}Yb and ^{165}Yb , on either side of ^{164}Yb , in which the two-quasiparticle energies are measured, we believe that at least to the first order this problem has been taken into account.

3.3. The positive parity bands in ^{164}Yb

The routhian for the ground-state band in ^{164}Yb is intersected by that of the S-band at $\hbar\omega \approx 0.28$ MeV (fig. 3), i.e. at this frequency, the ground-state band and the S-band interchange their character in the rotating frame. One of the interesting features at the bandcrossing is the interaction between the two bands. In cases where the

cascades along either or both bands branch off near the intersection, reliable values for the interaction strength can be obtained from the measured branching ratios. The strength obtained for the interaction between the g-band and the S-band in ^{164}Yb is about 90 keV.

The continuation of the ground-state band beyond the first crossing has been observed. This band undergoes a second crossing with other excited bands soon after the first crossing. According to the CSM prediction this crossing should correspond to the alignment of a second pair of $i_{13/2}$ quasineutrons, i. e. due to the crossing with a band based on the $(+,+)_2$ and $(+,-)_1$ intrinsic configurations. The gain in alignment in this crossing turns out to be larger than that obtained at the first crossing of the ground-state band ($\hbar\omega \approx 0.28$ MeV) which is supposed to have the largest alignment. This implies that the pertinent crossing involves more than two quasiparticles, i. e. it is a crossing between the g-band and a four-quasiparticle band. As to the nature of these two extra quasiparticles, blocking arguments can be used to show that they are also a pair of $i_{13/2}$ quasineutrons. The quasiproton alignment is not observed in the S-band up to the highest observed frequency of 0.42 MeV. As for the alignment of the lowest pair of negative parity quasineutrons, the $(-,+)_1$ and $(-,-)_1$ orbitals are blocked in all the negative parity side-bands. However, there would be no blocking in the yrast band. The non-observation of the alignment of a pair of negative parity quasineutrons in the S-band lends support to the conclusion that this second crossing in the

g-band is due to the exchange of character between the g-band and the ABCD band.

3.4. The negative parity bands in ^{164}Yb

3.4.1. General discussions

The interpretation of the negative parity bands is not fully straight-forward. Two major discrepancies are clearly seen when the experimental routhians of ^{164}Yb are compared with routhians constructed from the one-quasiparticle (fig. 5.) configurations of the adjacent odd-N isotopes. The energy splitting between the configurations $(-,1)_1$ and $(-,0)_1$ is much larger than expected and the alignment of the $(-,0)_2$ configuration is much too small. At $\hbar\omega=0.30$ MeV the alignment is about three units smaller than those of the $(-,0)_1$ and $(-,1)_1$ configurations. This is hardly consistent with the CSM interpretation of the three lowest negative parity bands as AE, AF and BE.

To get a better insight into the structure of the negative parity bands we have made a comparison with the corresponding bands in ^{166}Yb and $^{162,164}\text{Er}$. These bands are by far best known in ^{164}Er , where the low spin region has been studied in the (p,2n) and (α ,2n) reactions²⁰). The ^{164}Er data are shown in the lower left part of fig. 6. Three neutron-excited bands with negative parity and odd spins ($\alpha=1$) are known. At low frequencies the lowest of these bands is interpreted as the octupole-band. It is

crossed by a two-quasineutron band at $\hbar\omega \approx 0.18$ MeV. The crossing band has a $K=5$ bandhead and is interpreted as $5/2^+ [642]$ $5/2^- [523]$. A third $(-,1)$ band is also known in ^{164}Er , but the corresponding band has not been observed in any of the other nuclei. Two decay sequences with negative parity and even spins ($\alpha=0$) are known in ^{164}Er . The lower one, $(-,0)_1$, is obviously the signature partner of the $(-,1)_1$ band. The higher one, $(-,0)_2$, starts out with a small alignment at low frequencies ($i_x \approx 2\hbar$), but gains about $2.5\hbar$ in alignment in a limited frequency interval around $\hbar\omega = 0.20$ MeV (cf. fig. 6 and 7). This may be interpreted as a bandcrossing as illustrated in fig. 6. The interpretation of the neutron-excited bands in ^{164}Er is quite clear. At high frequencies the bands $(-,1)_1$, $(-,0)_1$ and $(-,0)_2$ have the properties of the CSM configurations AE, AF and BE, respectively. The two first of these bands are obviously built on a $K=5$ bandhead. The third one continues down to lower spins. In ref. ²⁰⁾ the low-spin part of this band is assigned as a $K=2$ band, and it is supposed to contain a considerable admixture of components from the $7/2^+ [633]$ and $3/2^- [521]$ neutron orbitals. The odd spin components of this configuration is supposed to form the $(-,1)_3$ band.

A two-quasiproton band, containing both odd and even spins, is also known in ^{164}Er (see fig. 6). It lies comparatively high in energy and has a very small alignment. The band starts from a $K=7$ bandhead and has the configuration $7/2^- [523]$ $7/2^+ [404]$.

Two bands with negative parity are known in ^{166}Yb . They are labelled $(-,1)_1$ and $(-,0)_1$ in fig. 6 and correspond to the CSM configurations AE and AF, respectively. Compared to the corresponding bands in ^{164}Er there are some differences. The $(-,1)_1$ decay sequence is interrupted at the 11^- state [cf. refs. 7,8)], from which the decay goes into the ground-state band and not to the lower states of the $(-,1)_1$ sequence. These states have, however, been identified via transitions to the ground-state band. The lowest observed state is 5^- , which presumably is the bandhead like in ^{164}Er . From the plot of the routhians it is seen that the $(-,1)_1$ routhian shows a tendency to bend down above the point where the $(-,1)_1$ sequence is interrupted, that is at $\hbar\omega=0.22$ MeV. One sees from the spectrum 7,8) that in particular the 11^- state is pushed down in energy. This behaviour can be understood if there exists an octupole-band in ^{166}Yb , which crosses and thereby interacts with the $(-,1)_1$ band at $\hbar\omega\approx 0.20$ MeV. The interaction must, however, be larger than that observed in ^{164}Er . That there is a non-negligible interaction between the octupole-band and $(-,1)_1$ band also in ^{164}Er is most clearly revealed in the alignment plot for the $(-,1)_1$ band (fig. 8), where a clear perturbation is seen in the frequency interval 0.13-0.20 MeV. This is also the interval where the decay sequence is interrupted in ^{166}Yb . At low frequencies the alignment of the $(-,1)_1$ and $(-,0)_1$ bands is slightly larger in ^{166}Yb than in ^{164}Er , but the difference becomes small at high frequencies.

A third side-band has been observed in ^{166}Yb . It was not

assigned a parity in refs. 7,8), but a comparison shows that this band is practically identical with the $(-,0)_2$ band in ^{164}Er , including the change in the alignment at $\hbar\omega \approx 0.18$ MeV. It has therefore been assigned $(-,0)_2$ in fig. 6.

The routhians of the $N=94$ isotones ^{162}Er and ^{164}Yb are quite different from those of the $N=96$ isotones. In particular the routhian of the $(-,1)_1$ band lies much lower than the routhians of the other bands. Furthermore the position of the $(-,0)_2$ routhian is lowered compared to the $(-,0)_1$ routhian. In fact the structure of the $(-,0)_1$ band changes dramatically at a frequency of about 0.20 MeV. We interpret this as a crossing of two bands with different characters as illustrated in fig. 6. In ^{162}Er both of the crossing bands have been observed below the crossing, while in ^{164}Yb only the lower one is seen. Above the crossing the properties of the $(-,0)_2$ band is very different in the two isotones.

As will be seen in the last section, the routhians of the negative parity bands cannot be well reproduced in CHFB calculations. In fact the results are more similar to those found experimentally in the $N=96$ isotones. Although the calculated energies are relatively similar for $N=94$ and $N=96$ the structure of the negative parity side-bands AE, AF, BE etc. is different, mainly because the $3/2^- [521]$ single particle level lies closest to the Fermi surface for $N=94$, while $5/2^- [523]$ is closest to the Fermi surface for $N=96$. These structural differences may critically

influence e. g. the interaction between the octupole-band and the two-quasiparticle band AE. Since such effects are not included in the CHFB model we shall here try to interpret the side-bands of the N=94 isotones by comparing them to the bands observed in the N=96 isotones rather than to the theoretically calculated bands.

3.4.2. The AF band

The $(-,0)_1$ band is most likely an almost pure two-quasineutron configuration, with the CSM assignment AF, above the band interaction at $\hbar\omega \approx 0.20$ MeV in both ^{162}Er and ^{164}Yb . In ^{162}Er the lower part of the $(-,0)_2$ band seems to form the continuation of the AF configuration below $\hbar\omega \approx 0.20$ MeV. The AF assignment is strongly supported by the alignment, which in the upper part of fig. 7 is compared to the alignment of the AF band in ^{164}Er and ^{166}Yb . The alignment agrees for the four nuclei within one unit at all frequencies and is also close to what one would expect theoretically. In ^{164}Yb a pronounced upbending is observed at $\hbar\omega = 0.31$ MeV. It must be interpreted as the crossing with the four-quasineutron configuration ABCF, which is expected to occur at roughly the observed frequency. No irregularity is observed in the three other nuclei up to $\hbar\omega = 0.323$ MeV, but this difference can be understood from differences in neutron number and deformation.

3.4.3. The low-spin part of the $(-,0)_1$ band

Below $\hbar\omega \approx 0.17$ MeV the $(-,0)_1$ bands in ^{162}Er and ^{164}Yb show a remarkable similarity with the low-spin part of the $(-,0)_2$ bands in ^{164}Er and ^{166}Yb , which can be seen from the alignment plot (lower part of fig. 7). The structure of these bands can therefore be expected to be similar. In ^{164}Er the $(-,0)_2$ band is known down to $I=2$ ²⁰). It is thus a low-K band. Its structure does probably not correspond to a simple two-quasineutron CSM configuration, but is of a more complex character, involving important components of the $3/2^- [521]$ level ²⁰). If this structure is preserved in the $N=94$ isotones it seems natural that the band goes down in energy for $N=94$, where it belongs to the $(-,0)_1$ decay sequence and not to the $(-,0)_2$ sequence as for $N=96$. Except in ^{164}Er the band is only known down to $I=4$. This does not exclude the existence of lower spin states, since such states may not be populated in the heavy-ion reactions used. Also in ^{164}Er the lowest states of the band are not seen in these experiments ^{21,22}).

3.4.4. The $(-,1)_1$ band

This band is identified as the AE two-quasineutron CSM configuration in ^{164}Er and ^{166}Yb , although it is slightly perturbed by the crossing with the octupole-band. It is furthermore clear that the $(-,1)_1$ band in ^{162}Er in fact is the octupole-band at low spins. The pure AE band must lie close to the AF band also in the $N=94$ isotones. It is then immediately seen from fig. 6 that the octupole-band and a

possible AE band have to be much more separated in energy in ^{162}Er than in ^{164}Er . A hypothetical crossing between a pure octupole-band and a pure AE band in ^{162}Er must therefore occur at a considerably higher frequency in ^{162}Er (not below $\hbar\omega=0.25$ MeV) than in ^{164}Er ($\hbar\omega=0.175$ MeV). It may also be that the octupole-band in ^{162}Er contains important components of the pure AE configuration, at least at high spins, which simply means that there is a large interaction between these two bands. In fact the $(-,1)_1$ band never reaches the pure AE structure, which can be seen from the separation of the $(-,1)_1$ and $(-,0)_1$ routhians, which is still about 0.20 MeV at the highest frequency at which both bands are known ($\hbar\omega=0.322$ MeV).

The $(-,1)_1$ band in ^{164}Yb is very similar to the corresponding band in ^{162}Er . Although it is only known down to $I=5$ we believe that this band has to begin as the octupole-band at low frequencies. At higher frequencies it interacts strongly with the unobserved AE band and obtains an increasingly pure two-quasiparticle structure. The pure AE structure is, however, never reached. The gradual development of the octupole-band into a two-quasiparticle band has been predicted theoretically by Vogel ²³).

The above interpretation of the $(-,1)_1$ bands implies that the interaction between the octupole-band and the AE band is very different for $N=96$ and $N=94$. It is obvious that such a difference can arise from the structural differences in the bands, caused by the changed position

of the Fermi energy. There is, however, no theoretical proof so far that this actually is the case.

It is also useful to study the alignment of the $(-,1)_1$ bands (fig. 8). Both the N=94 isotones show an alignment at low frequencies which lies between that of the AE band and the octupole-band in ^{164}Er . At high frequencies the band in ^{162}Er has an alignment very similar to those of the N=96 isotones, while the band in ^{164}Yb shows a gradual increase of the alignment at high frequencies. This is in a qualitative agreement with the observations made for the AF band, where a strong upbend was observed at $\hbar\omega=0.31$ MeV in ^{164}Yb but not in the other nuclei. The reason why the $(-,1)_1$ band in ^{164}Yb does not also show a sharp upbend is not fully clear, but must be connected with the fact that it does not correspond to a pure AE configuration.

3.4.5. The $(-,0)_2$ band

In ^{164}Er and ^{166}Yb this band has at high frequencies ($\hbar\omega \approx 0.20$ MeV) the properties expected for the CSM configuration BE. However, in the N=94 isotones the $(-,0)_2$ band looks quite different. In ^{162}Er it lies lower in energy and has a larger alignment while the opposite is true for ^{164}Yb (see lower part of fig. 7). In fact the differences are so big that it can be excluded that the $(-,0)_2$ band corresponds to the BE configuration in all four nuclei. Based on CSM calculations as well as on the experimental one-quasiparticle routhians for ^{163}Yb [ref.¹⁰)] we can predict that the AG band must lie very

close to the BE band in the $N=94$ isotones. Assuming a certain interaction between these two bands could possibly explain the low energy of the $(-,0)_2$ band in ^{162}Er but not the high energy in ^{164}Yb .

In fact it is very hard to understand the structure of the $(-,0)_2$ band in ^{164}Yb . We see from fig. 6 that the $(-,0)_2$ band seems to form a smooth continuation of the lower part of the $(-,0)_1$ band and may therefore have a similar structure. We also see that the band shows no irregularity at the AB crossing ($\hbar\omega=0.28$ MeV) nor at the BC crossing ($\hbar\omega=0.31$ MeV). This would be the case if the B level is occupied. The first bandcrossing in such a band (AD) would then lie somewhat above the BC crossing, possibly above the highest observed frequency.

Another possibility is that the $(-,0)_2$ band is a two-quasiproton configuration. The relatively high energy of the routhian would be consistent with this interpretation (cf. the proton band in ^{164}Er , fig. 6). In order to account for the alignment ($\approx 4.3\hbar$) a possible proton configuration must include the $1/2^- [541]$ orbital, which is the only one with sufficiently large alignment in the near-lying odd- Z nuclei. From the experimental routhians of ^{165}Lu [ref.²⁴] one can conclude that the most likely configuration is $1/2^- [541; \alpha=1/2]$ $1/2^+ [411; \alpha=-1/2]$. It is at high frequencies the lowest configuration with the right parity and signature and has the right alignment ($i_x \approx 3.5\hbar + 0.8\hbar = 4.3\hbar$). A configuration with $1/2^- [541]$ occupied is also expected to have a delayed backbending.

In ^{165}Lu the $1/2^- [541]$ band does not backbend before $\hbar\omega = 0.32$ MeV, and in ^{182}Os [ref. 25)] the proton band assigned $1/2^- [541]$ $9/2^- [514]$ backbends at $\hbar\omega \geq 0.34$ MeV, while the ground-state band S-band crossing lies at $\hbar\omega = 0.256$ MeV. The interpretation of the $(-,0)_2$ band as a proton configuration could therefore be consistent with the fact that no backbending is observed.

The interpretation of $(-,0)_2$ as a proton configuration could also explain why this band is observed although it lies very high in energy, because it would retard the decay from this band down to the lower-lying neutron configurations. In fact the assignment $(-,0)_2$ is misleading, because there must be at least two $(-,0)$ configurations which are lower in energy, namely AF and ABCF (cf. fig. 6).

The interpretation of the $(-,0)_2$ band as a proton band gives rise to some questions. Is the lower part of the $(-,0)_1$ band the neutron configuration previously suggested or is it just the continuation of the proton band? Secondly, are the observed transitions between the $(-,0)_2$ and $(-,0)_1$ bands consistent with $(-,0)_2$ being a proton band? Comparisons with ^{164}Er and ^{182}Os suggest that it could be so.

3.5. A summary of the crossing frequencies and the gain in alignment in Yb nuclei

Much data is now available for Yb isotopes for

bandcrossing frequencies and gain in alignment at the bandcrossings. Therefore it might be appropriate to summarize these results and to discuss some of the observed systematical behaviour. The crossing frequency $\hbar\omega_c$ is defined as the frequency at which routhians of seniority ν and seniority $\nu+2$ cross ²⁶⁾. The gain in alignment Δi is defined at $\hbar\omega_c$ between the two systems ν and $\nu+2$. Defined in this way the crossing frequency and the gain in alignment are nearly reference independent.

The data for the AB crossing are presented in table 3. The AB crossing is a crossing between zero- and two-quasiparticle configurations in the even-N isotopes and between one- and three-quasiparticle configurations in the odd-N isotopes. The crossing frequency is lower for the odd-N isotopes than for the even-N isotopes. This is due to a reduction of the pairing correlation parameter in the odd-N nuclei ²⁶⁾. The reduction is a result of the blocking of the pairing contribution from a quasineutron orbit near the Fermi surface. This reduction is almost the same for all the odd-N Yb isotopes due to the fact that all the valence orbits have nearly the same shape and therefore contribute in the same way to the pairing ²⁷⁾. There is also a reduction in Δi for the odd-N Yb isotopes compared with the even ones. This is due to the fact that reduced pairing reduces the compression of the single particle levels and therefore reduces the mixing of low- Ω orbits into the lowest orbit of a particular configuration.

A survey of the neutron levels for $^{160,162,164,166}\text{Yb}$ near the Fermi level (see fig. 9) shows that the highly alignable high- j low- Ω orbitals originating from the $i_{13/2}$ shell model states lie nearest to the Fermi surface in ^{160}Yb and that they gradually shift away from the Fermi level with increasing neutron number. The change of the high- Ω components of the $i_{13/2}$ orbitals implies that the gain in alignment at the AB crossing should decrease with increasing neutron number, disregarding possible changes in the neutron pairing correlation parameter. This is indeed observed to be the case (cf. table 3).

Table 4 contains data appropriate for the BC crossings. The data for these crossings is not as complete as for the AB crossing. When comparing the crossing frequencies for crossings between zero- and two-, one- and three- and two- and four-quasiparticle configurations the blocking argument seems to work for most of the nuclei. However, near $N=90$ the relation between the crossing frequencies is inverted ¹⁹⁾ $[\hbar\omega_c(0-2qp) < \hbar\omega_c(1-3qp) < \hbar\omega_c(2-4qp)]$. In this case the blocking argument does not work. This is not well understood at the moment, but it could be pointed out that there are changes in deformation in the different bands in ^{160}Yb 28,29).

The ground-state bands in $^{160,162,164,166}\text{Yb}$ cross other excited bands soon after the AB crossing. Except for the case of ^{166}Yb , it has been possible to follow the bands above this second crossing high enough to be able to extract the crossing frequencies with some confidence and

to get some insight into the gain of alignment due to this crossing. For ^{162}Yb as well as the earlier discussed ^{164}Yb the gain in alignment implies that this crossing involves more than two quasiparticles.

It can be seen that the crossing frequencies in the side-bands of $^{160,162,164,166}\text{Yb}$ are considerably higher than those in the yrast bands. This is a reflection of the fact that the two-quasineutron side-bands involve either the $(+,+)_1$ or $(+,-)_1$ $i_{13/2}$ valence quasineutron configuration together with a negative parity valence quasineutron. Consequently, the bandcrossings observed in these bands are due to the alignment of another pair of $i_{13/2}$ neutrons than those responsible for the first bandcrossing in the yrast bands of the even-even isotopes or in the negative parity bands of the neighbouring odd-N isotopes.

3.6. Comparison of experimental results to CSM calculations

We have made some preliminary self-consistent CSM calculations for ^{164}Yb [see ref. 30)]. While the calculated pairing gap is of the order of the odd-even mass difference in the 0^+ ground-state it is considerably reduced in the two-quasiparticle bands and is in the upper part of the negative parity side-bands typically about 700 keV. The details of the calculations will not be discussed here, but we show in fig.10 the theoretical routhians for a number of two- and four-quasiparticle configurations.

The figure is constructed for $\Delta=830$ keV, which is a representative value for the two-quasiparticle bands. The theoretical routhians have been shifted up in energy to a position which gives an approximate agreement between the theoretical and experimental S-bands. The shift is qualitatively justified by the fact that the g-band and the S-band have different Δ values [cf. ref. 29)]. It also simplifies the comparison with experiment, where we are mainly interested in the relative energies of the two-quasiparticle routhians. Fig. 10 confirms the conclusions already drawn in the previous sections. The experimental AF routhians (crosses) agree fairly well with the corresponding theoretical routhian. Also the crossing with the ABCF routhian is in good agreement with the calculations. There is, however, no theoretical correspondence to the $(-,1)_1$ routhian (filled circles). The lowest theoretical $(-,1)$ routhian, which is AE, lies much higher in energy and has a different slope. This confirms that $(-,1)_1$ is not a simple two-quasiparticle state. The $(-,0)_2$ routhian (filled squares) finally, has an energy which is not too different from that of the theoretical AG and BE configurations. The slope is, however, very different, which suggests that the $(-,0)_2$ band must have a different configuration.

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Table 1

The γ -ray energies, intensities, angular distribution and conversion electron coefficients for transitions assigned to ^{164}Yb following the $^{152}\text{Sm}(^{16}\text{O}, 4n)$ reaction at 81 MeV.

E_γ (keV)	I_γ^{rel} b)	Ang. dist. coeff. ^{c)}		$\alpha_K^{\text{d)}$ ($\times 10^{-3}$)	Assignments	
		A_2/A_0	A_4/A_0		I_1^π	I_f^π
123.3					2^+	0^+
187	weak				14^{+-}	14^+
247.6	$10^{\text{e)}$				6^-	4^-
262.2	1055	0.27(01)	-0.07(01)		4^+	2^+
287	weak				unassigned	
291.1	8	-0.28(02)	0.22(09)		15^-	14^{+-}
325.0	50	0.31(02)	-0.11(02)		8^-	6^-
325	weak				9^-	7^-
354	16	0.24(05)	0.03(05)		12^{+-}	12^+
356.5	15	0.33(05)	0.09(05)		6^-	5^-
359.9	53	0.31(02)	-0.06(02)	35(08)	10^-	8^-
374.7	1000	0.28(01)	-0.08(01)		6^+	4^+
381.1	52	0.31(04)	-0.05(04)		12^-	10^-
401.2	31	0.21(04)	0.03(04)		11^-	9^-
403	6	0.34(14)	0.03(13)		14^{+-}	12^{+-}
415.0	20	0.30(06)	-0.04(06)		10^-	8^-
449	19	0.59(08)	0.23(07)		8^-	7^-

Table 1 (continued)

E_γ ^{a)} (keV)	I_γ ^{rel b)}	Ang. dist. coeff. ^{c)}		α_K ^{d)} ($\times 10^{-3}$)	Assignments		
		A_2/A_0	A_4/A_0		I_i^π	I_f^π	
452	100	0.24(02)	-0.05(02)	7.3(20)	6^-	5^+	
453.3					14^-	12^-	
455					14^-	13^-	
463	975	0.30(01)	-0.07(01)		13^-	11^-	
463.1					8^+	6^+	
464					12^-	11^-	
474	weak					unassigned	
484.3	28	0.47(05)	0.18(05)		10^-	9^-	
489.8	206	0.30(01)	-0.08(01)		16^+	14^+	
491.8	15 ^{e)}				12^-	10^-	
514.4	106	0.26(02)	-0.12(02)		15^-	13^-	
530.4	735	0.31(01)	-0.08(01)		10^+	8^+	
532.4	79 ^{e)}	-0.08(04)	-0.08(04)		16^-	14^-	
533.4					13^-	12^+	
543.2	117	0.29(01)	-0.11(01)		18^+	16^+	
562.6	10 ^{e)}				14^-	12^-	
564.1	50 ^{e)}	>0			17^-	15^-	
569.4	305	0.32(01)	-0.08(01)		14^+	12^+	
576.6	446	0.29(01)	-0.09(01)		12^+	10^+	
596.2	30 ^{e)}				18^-	16^-	
609	16 ^{e)}	0.27(06)	-0.14(06)		16^+	14^+	
610.3	24 ^{e)}				19^-	17^-	

Table 1 (continued)

$E_Y^a)$ (keV)	$I_Y^{\text{rel } b)}$	Ang. dist. coeff. ^{c)}		$\alpha_K^d)$ ($\times 10^{-3}$)	Assignments I_1^π I_f^π	
622	}			8.6(10)	22 ⁻	20 ⁻
622					20 ⁻	18 ⁻
633.3	57	0.31(04)	-0.13(04)		20 ⁺	18 ⁺
638	5 ^{e)}				16 ⁻	14 ⁻
647.3	142	-0.17(01)	-0.04(01)	<4.2	11 ⁻	10 ⁺
653.7	20	0.42(08)	-0.19(08)		21 ⁻	19 ⁻
683	weak				(24 ⁻)	22 ⁻
696	18			5.0(15)	18 ⁺	16 ⁺
702	}			5.5(15)	23 ⁻	21 ⁻
702					18 ⁻	16 ⁻
707	}			6.7(15)	20 ⁺	18 ⁺
707					22 ⁺	20 ⁺
712.5	30 ^{e)}	Doppler broadened		5.0(15)	22 ⁺	20 ⁺
738	weak					6 ⁺
745	weak					8 ⁺
756.7	55	0.27(03)	-0.02(02)	4.6(15)	14 ⁺	12 ⁺
776.5	93	-0.20(01)	0.02(02)	1.8(6)	9 ⁻	8 ⁺
780.3	14 ^{e)}	0.26(07)	-0.06(07)	>3.3	24 ⁺	22 ⁺
785.5	weak				10 ⁻	10 ⁺
796.6	24	0.41(04)	-0.09(04)	>3.7	16 ⁺	14 ⁺
839		Doppler broadened			(26 ⁺)	24 ⁺
901	20	0.34(06)	0.02(06)	<3.0	8 ⁻	8 ⁺

Table 1 (continued)

E_Y (keV)	I_Y a)	rel b)	Ang. dist. coeff. c)		α_K d)	Assignments	
			A_2/A_0	A_4/A_0		I_I	I_P
915	36		-0.46(08)	0.08(07)	<2.5	7 ⁻	6 ⁺
930	22		0.30(04)	0.00(04)	4.5(8)	12 ⁺	10 ⁺
962	42		-0.18(04)	0.03(04)	4.2(8)	5 ⁺	4 ⁺
1039	15		0.51(10)	0.05(09)		6 ⁻	6 ⁺
1058	15		-0.31(06)	0.07(06)		5 ⁻	4 ⁺
1114	weak						8 ⁺
1166	10 ^{e)}					4 ⁻	4 ⁺

a) Energies are accurate to 0.2 keV for strong transitions (rel. int. > 50), increasing to about 0.5 keV for weaker transitions.

b) Intensities are given relative to the 374.7 keV $6^+ \rightarrow 4^+$ transition.

c) Only fitting errors are given.

d) Normalised to the K-conv. coeff. of the 374.7 and 633.3 keV E2 transitions.

e) From coincidence data at 84 MeV. Rel. int. not corrected for the angular correlation effects.

Table 2

Values extracted for the pairgap parameter Δ and the residual interaction between quasiparticles $V_{\mu\nu}$ at three different frequencies.

$\hbar\omega$ (MeV)	0.22	0.25	0.28
Δ (MeV)	1.056	1.074	1.085
V_{AB} (MeV)	-0.076	-0.087	-0.087
V_{AE} (MeV)	-0.231	-0.206	-0.195
V_{BE} (MeV)	-0.135	-0.114	-0.078
V_{BF} (MeV)	-0.460	-0.378	-0.336

Table 3

The crossing frequencies for the AB crossing and the gain in alignment at this crossing for $^{160-168}\text{Yb}$.

Nucleus	$\hbar\omega_c$	Δi	Ref.
^{160}Yb	0.269	11.0	3
^{161}Yb	0.235	9.0	4,5
^{162}Yb	0.269	9.9	4,5
^{163}Yb	0.232	7.5	10
^{164}Yb	0.276	8.2	present work
^{165}Yb	0.226	8.1	9
^{166}Yb	0.275	8.0	7,8
^{167}Yb	0.238	6.7	9
^{168}Yb	0.27	>6.5	31

Table 4

The crossing frequencies for the BC crossings and the gain in alignment at these crossings for $^{160-167}\text{Yb}$.

Nucleus	Config.	$\hbar\omega_c$	Δi	Ref.
^{160}Yb	O-BC	0.34	7.6	3,32
	AE-AEBC	0.38	6.6	
	AF-AFBC	0.36	6	
^{161}Yb	A-ABC	0.35	6.5	4,5
^{162}Yb	O-BC	0.30	11	4,5
	AE-AEBC	0.33	>4	
	AF-AFBC	0.33	>4	
^{163}Yb	A-ABC	0.35	>4	10
^{164}Yb	O-BC	0.35	8.2	present work
	AF-AFBC	0.31	3.3	
^{165}Yb	A-ABC	0.36	4.3	9,33
^{166}Yb	O-BC	0.35	>3	7,8
^{167}Yb	A-ABC	0.33	>2.5	9

Figure captions

- Fig. 1. Examples of γ - γ coincidence spectra from the $^{152}\text{Sm}(^{16}\text{O},4n)^{164}\text{Yb}$ reaction at 84 MeV.
- Fig. 2. Level scheme of ^{164}Yb showing states populated in the $^{152}\text{Sm}(^{16}\text{O},4n)^{164}\text{Yb}$ reaction at 84 MeV.
- Fig. 3. Experimental routhians for different bands in ^{164}Yb , referred to the reference configuration determined by the Harris parameters $\mathcal{J}_0 = 25.8 \text{ MeV}^{-1}\hbar^2$ and $\mathcal{J}_1 = 90 \text{ MeV}^{-3}\hbar^4$. The routhians are corrected for the g-band S-band interaction of 90 keV.
- Fig. 4. Experimental alignment for the different bands in ^{164}Yb . The reference parameters are the same as in fig. 3.
- Fig. 5. Experimental routhians for $^{163,165}\text{Yb}$ are shown in the upper half of the figure. In the lower half of the figure, constructed two-quasineutron configurations are shown (solid lines) and their extrapolations (dashed lines). The residual interaction is not included in the constructed routhians. The constructed routhians were shifted up by a constant term $2\Delta_n^{\text{ce}} = 2.10 \text{ MeV}$. The points plotted together with the constructed routhians are the experimental two-quasineutron configurations in ^{164}Yb . See fig. 3.
- Fig. 6. The experimental routhians for $^{162,164}\text{Er}$ and

$^{164,166}\text{Yb}$. The corresponding bands in these four nuclei are marked in the same way. The data used are for ^{162}Er from ref. 34), for ^{164}Er from ref. 22) and for ^{166}Yb from ref. 8). Some low-spin states are from ref. 15).

Fig. 7. Alignment plots for $^{162,164}\text{Er}$ and $^{164,166}\text{Yb}$.

The large symbols are referring to the bands marked with the corresponding symbols in fig. 6. For references see figure caption 6.

Fig. 8. Alignment plots for $^{162,164}\text{Er}$ and $^{164,166}\text{Yb}$.

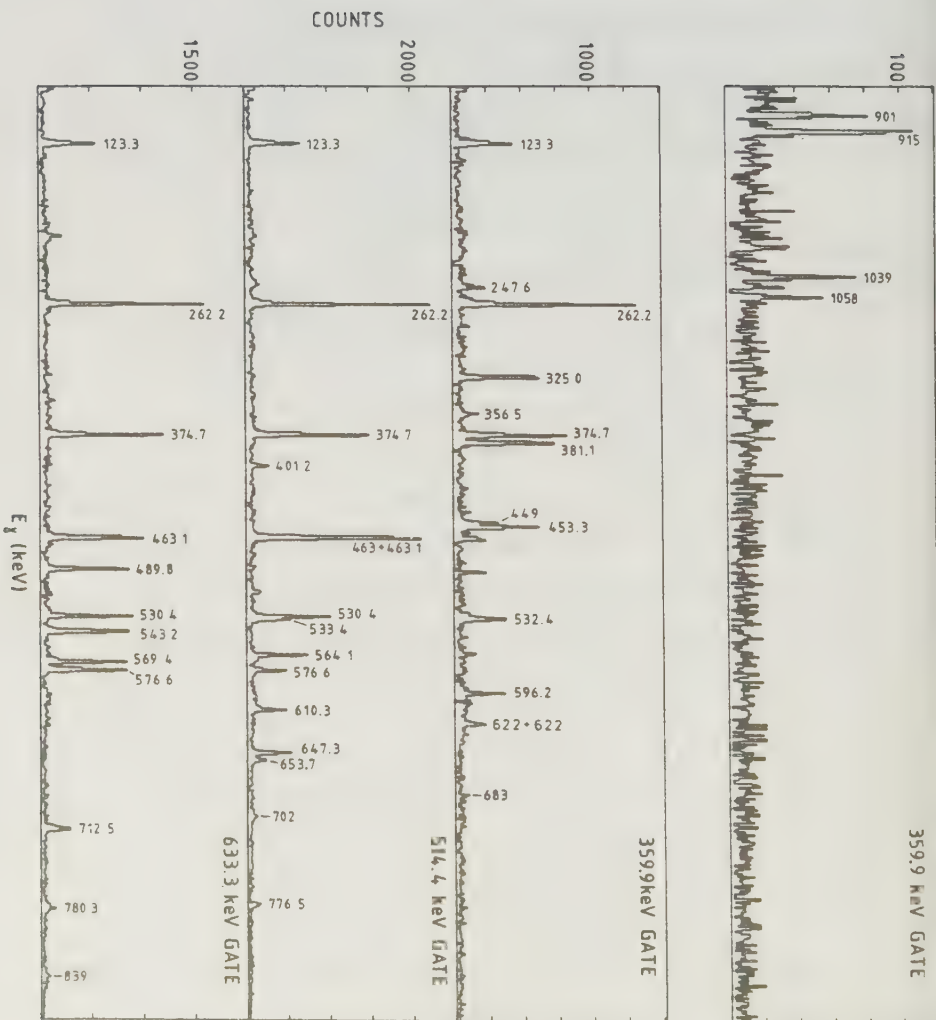
The large symbols are referring to the bands marked with the corresponding symbols in fig. 6. For references see figure caption 6.

Fig. 9. Nilsson states near the Fermi surface for $^{160,162,164,166}\text{Yb}$. The position of the Fermi surface is labelled by λ .

Fig. 10. Theoretical and experimental routhians for ^{164}Yb .

The theoretical routhians have been shifted upwards by 0.6 MeV. For the notation of the experimental points see fig. 3.

Fig. 1



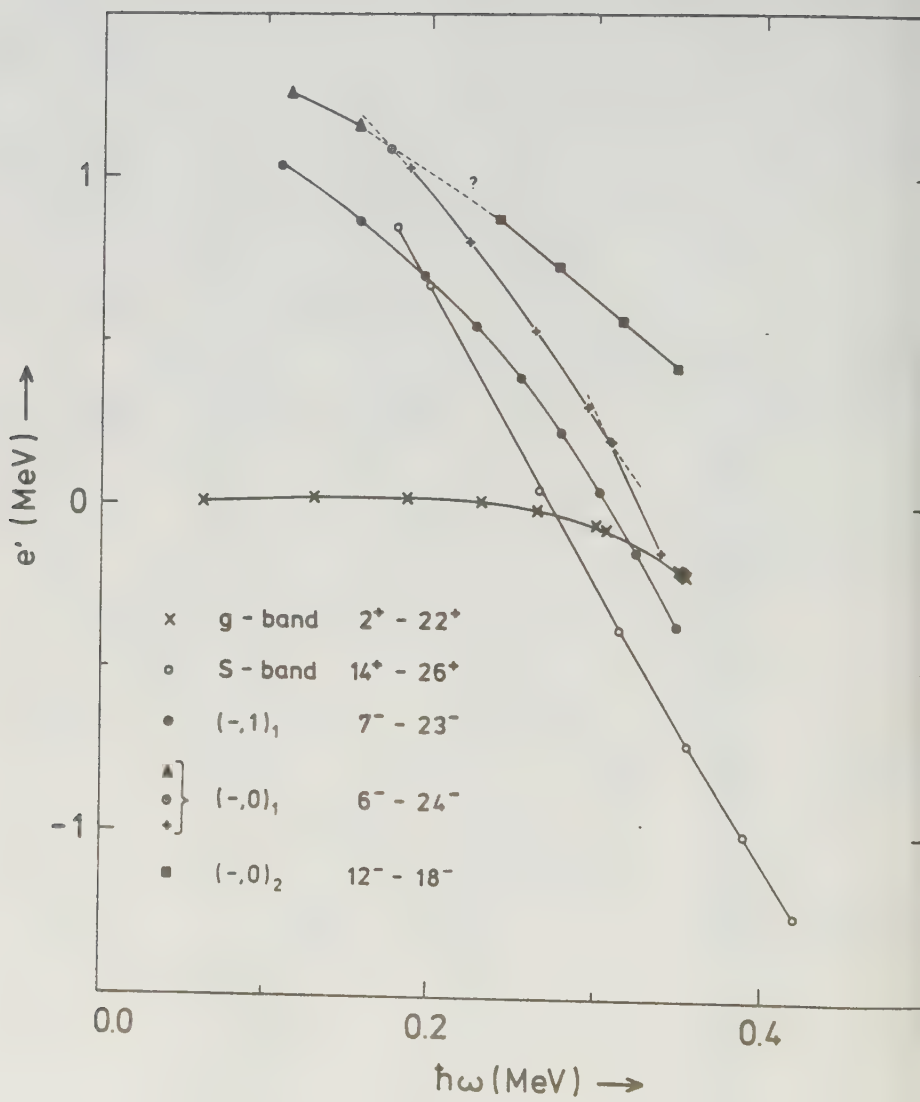


FIG. 3

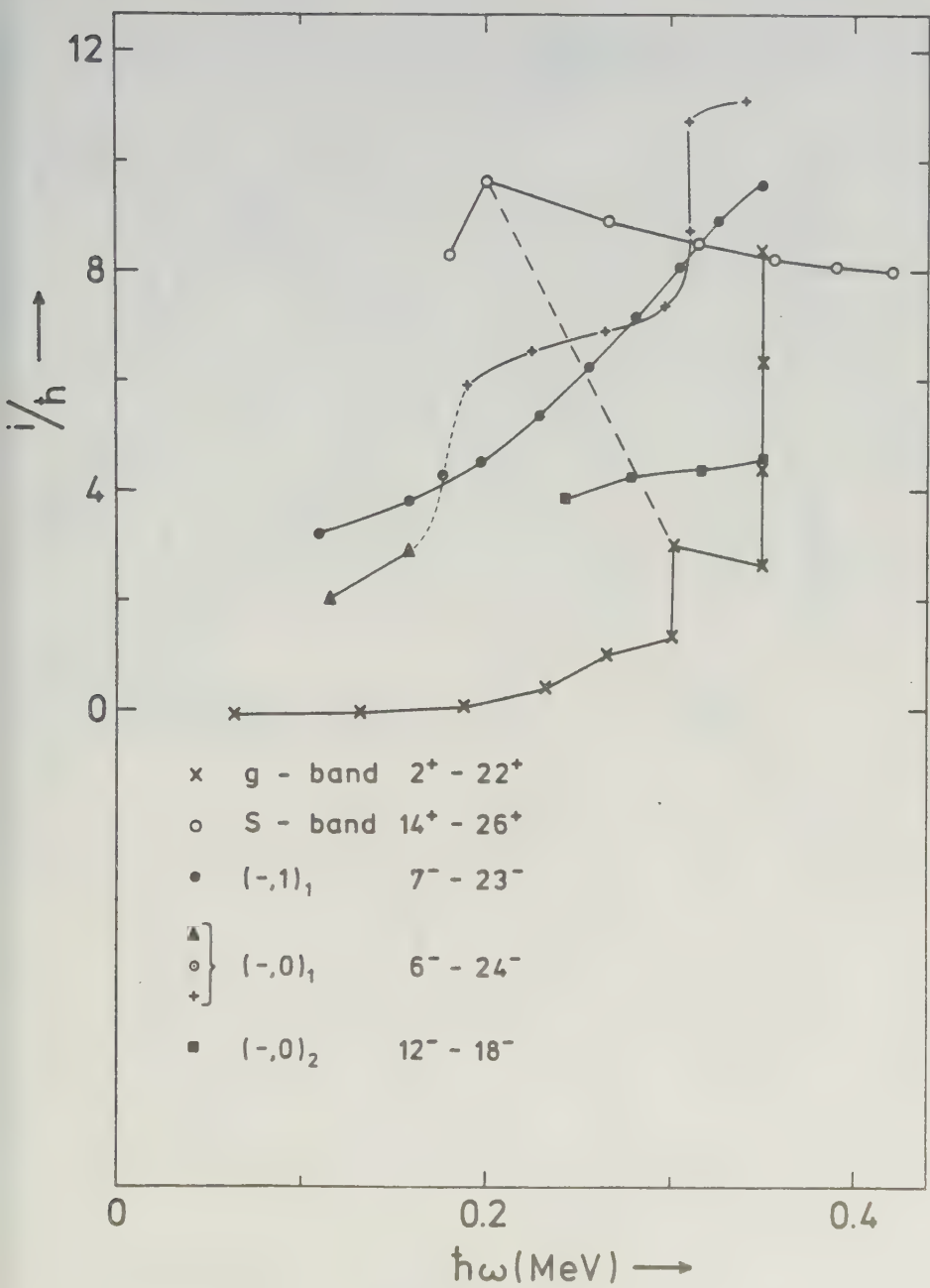


FIG. 4

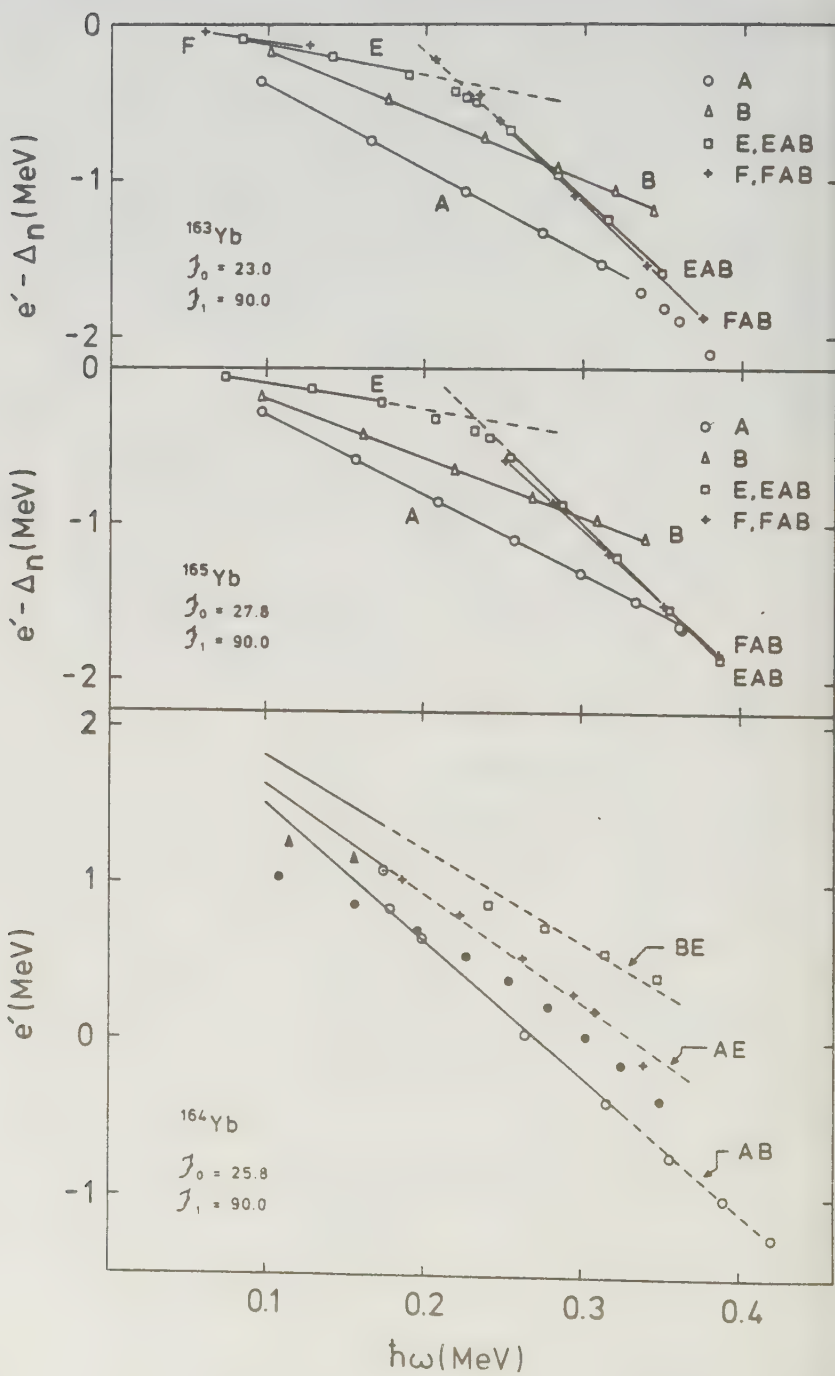


FIG. 5

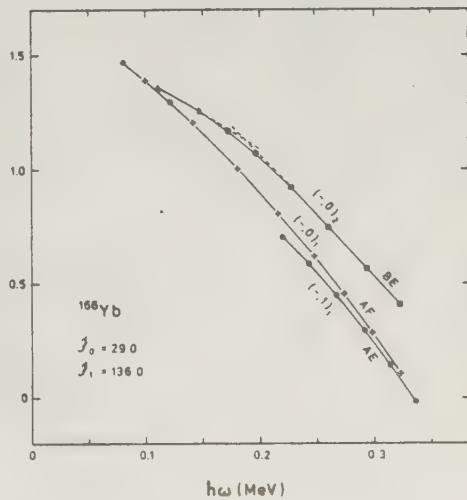
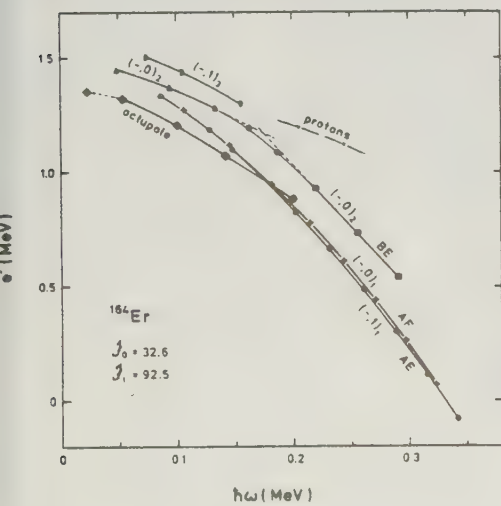
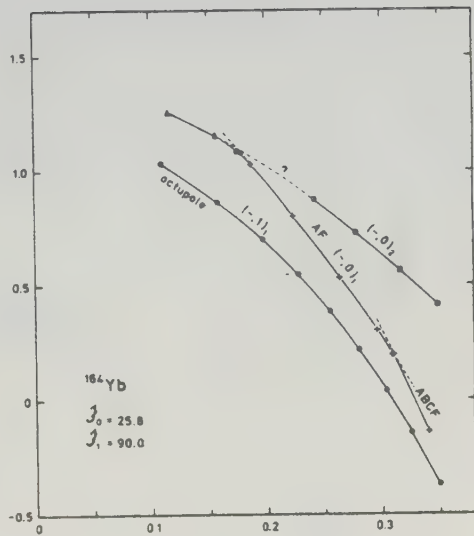
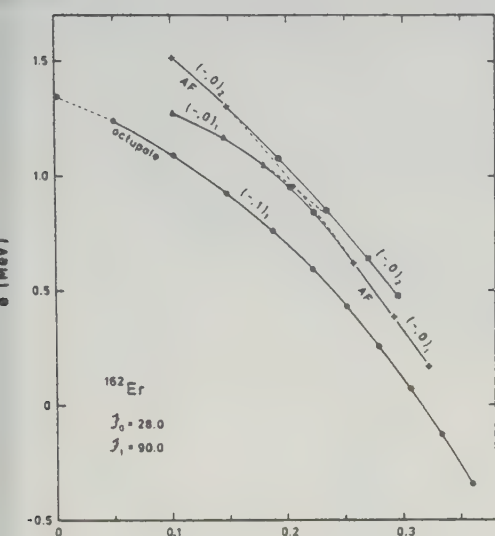


FIG. 6

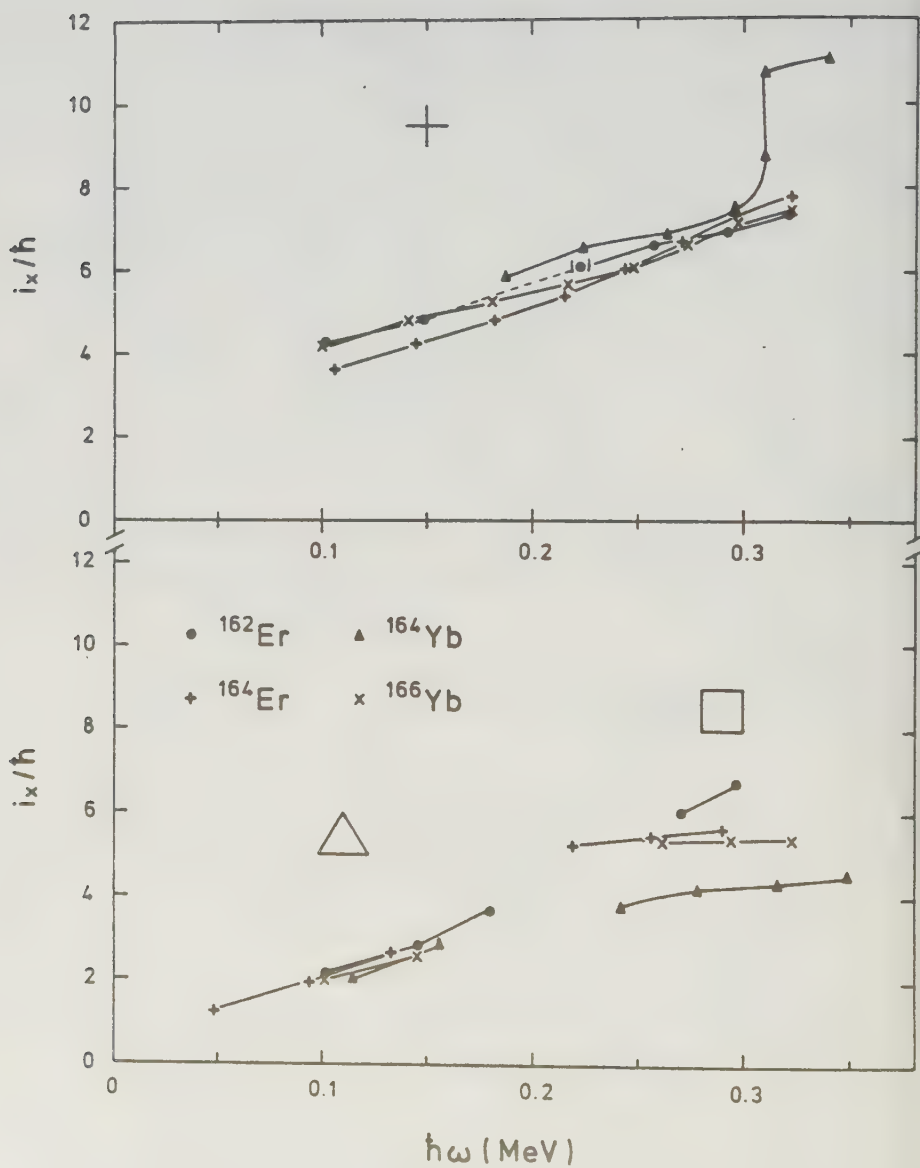


FIG. 7

FIG. 8

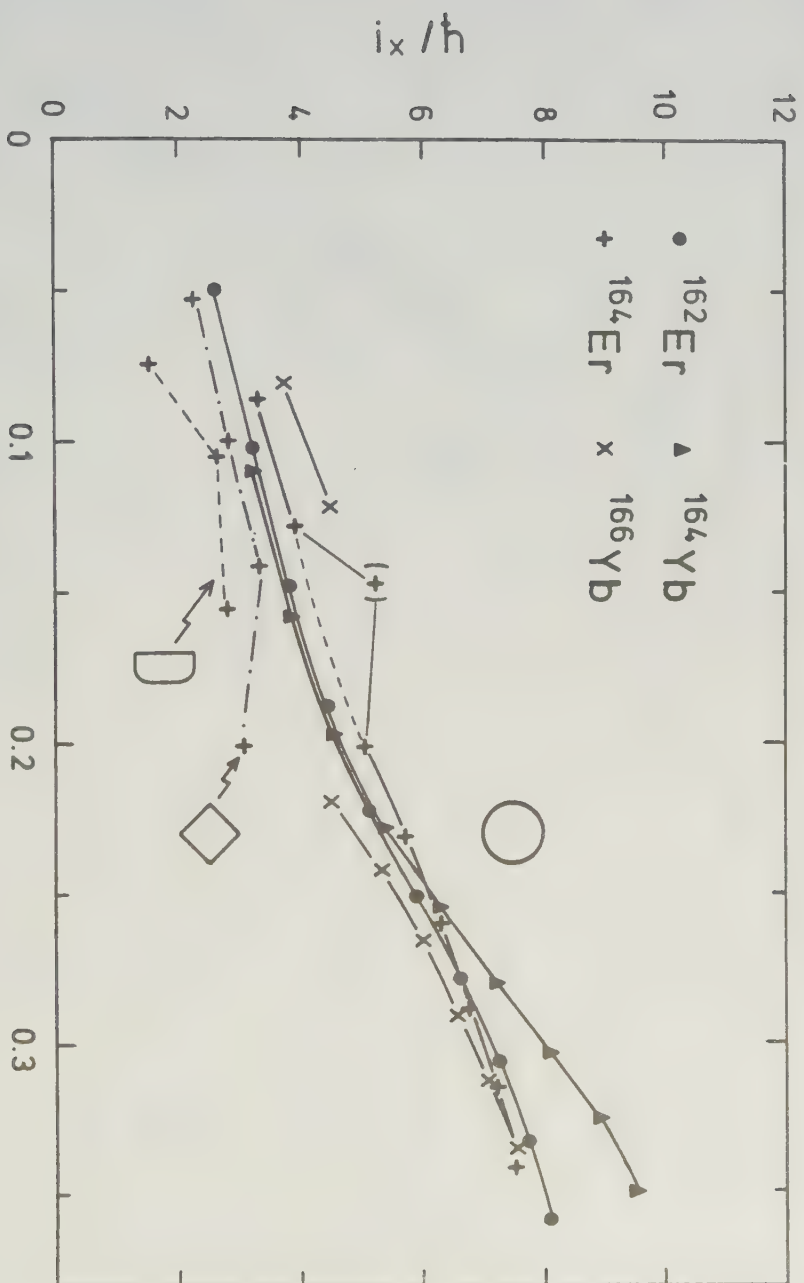
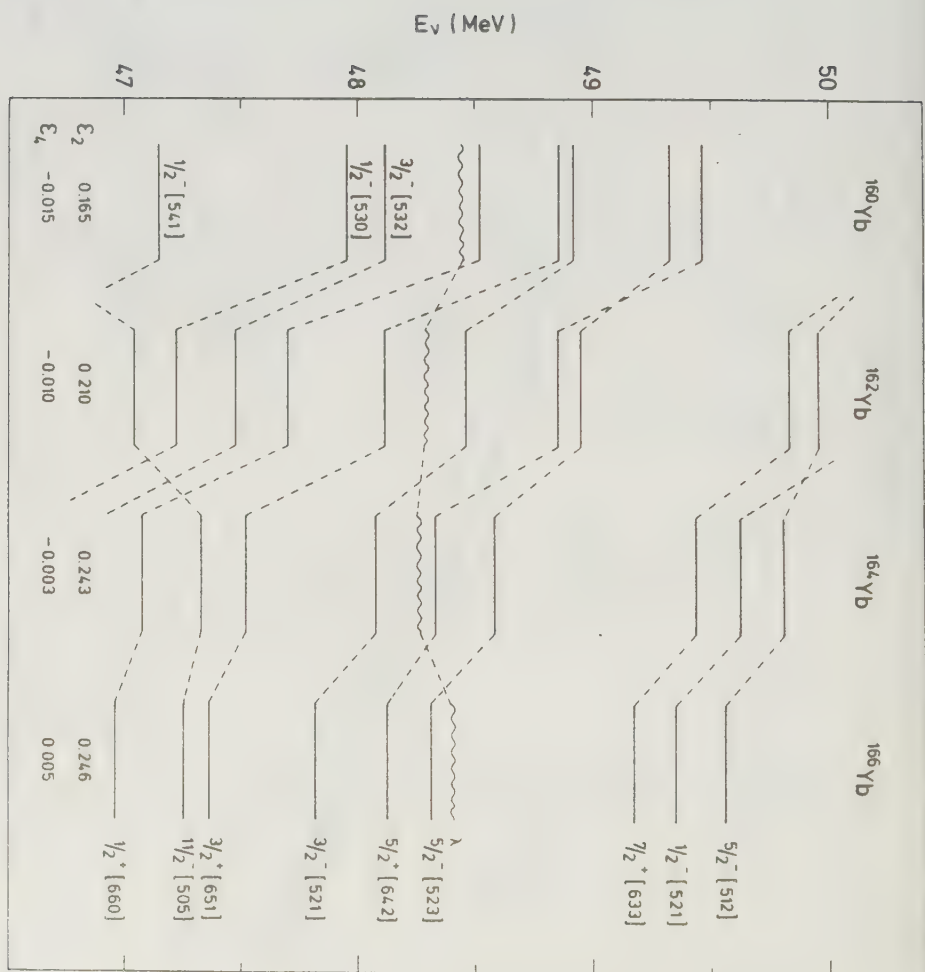


FIG. 9



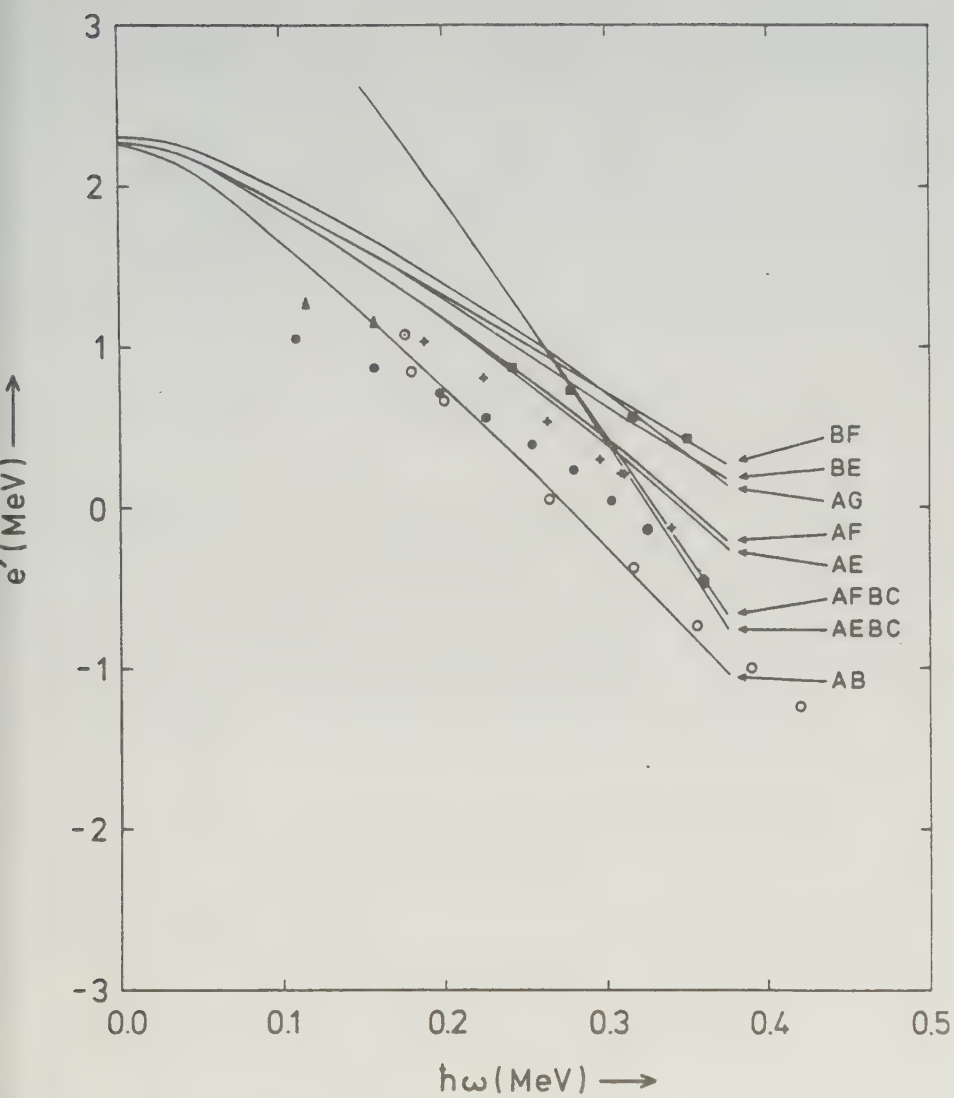


FIG. 10

Dokumentutgivare
UNIVERSITY OF LUND
Handläggare
Department of Physics &
Mathematical Physics

Dokumentnamn
Internal report
Utgivningsdatum
March 1983

Dokumentbeteckning
LUNFD6/(NFFK-7027)
Ärendebeteckning

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Dokumenttitel och undertitel

Near-Yrast spectroscopy of ^{164}Yb and Neighbouring Nuclei.

Referat (sammandrag)

High-spin states in ^{164}Yb have been populated in the $^{152}\text{Sm}(^{16}\text{O},4n)$ and $^{150}\text{Sm}(^{18}\text{O},4n)$ reactions. From studies of γ - γ coincidences, γ -ray angular distributions and conversion electron measurements the level scheme has been constructed. The g-band and the S-band have been established to spin and parity 22^+ and 26^+ , respectively, and the rotational sequences $(\pi, \alpha) = (-, 1)_1$, $(-, 0)_1$ and $(-, 0)_2$ to 23^- , 24^- and 18^- , respectively. The side-bands in $^{162}, ^{164}\text{Er}$ and $^{164}, ^{166}\text{Yb}$ are discussed. Constructed two-quasineutron configurations and cranked shell model (CSM) calculations are compared with the experimental results in ^{164}Yb . Residual interactions between quasiparticles in ^{164}Yb are calculated. Crossing frequencies and the gain in alignment are summarized for the Yb isotopes and the main features are discussed.

Referat skrivet av

The authors

Förslag till ytterligare nyckelord

Klassifikationssystem och -klass(er)

Indextermer (ange källa)

Omfång 39 pages
10 figures
Språk English
Sekretessuppgifter

Övriga bibliografiska uppgifter

ISSN 0348-9329

ISBN

Mottagarens uppgifter

Dokumentet kan erhållas från
Department of Cosmic & Subatomic Physics
University of Lund
Sölvegatan 14, S-223 62 LUND, Sweden.

Preis

Blankett LU 11:25 1976-07

COSMIC AND SUBATOMIC PHYSICS REPORT
LUIP 8305
MARCH 1983
LUNFD6/(NFFK-7028)1-21(1983)
ISSN 0348-9329

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Abstract: High-spin states in ^{165}Lu have been populated in the $^{153}\text{Eu}(^{16}\text{O}, 4n)$ reaction. An excitation function measurement was made to assign correct γ -rays to ^{165}Lu . A level scheme was constructed from the studies of γ - γ coincidences, and the measurement of γ -ray angular distributions. Five rotational bands have been assigned to ^{165}Lu , and identified as the ones built on the $5/2^+(402)$, $1/2^+(411)$, $1/2^-(541)$, $7/2^+(404)$ and $9/2^-(514)$ Nilsson states. Both signatures are seen for all of them except the one built on the $1/2^-(541)$ Nilsson orbital. The crossing frequencies, for the bands observed above backbending, are determined and the variation in the crossing frequency is discussed.

NUCLEAR REACTIONS: $^{153}\text{Eu}(^{16}\text{O}, 4n)$. $E=73\text{--}85$ MeV; measured γ - γ coinc., $\gamma(\theta)$, $I_\gamma(E)$, γ -time; ^{165}Lu deduced levels, J , π , alignments. Enriched targets, $\text{Ge}(\text{Li})$ detectors. Compton-suppressed $\text{Ge}(\text{Li})$ coincidence set-up.

1. Introduction

Recently, detailed spectroscopic studies of even-even and odd-N deformed nuclei have been performed. Thus, the level structure of a series of Ytterbium nuclei have been investigated¹⁻⁹). On the other hand little information is available for odd-Z nuclei at and above the backbending region. It is of great interest to establish similar systematics for the quasiproton states as has been done earlier for the quasineutron states. In addition, the magnetic transition probabilities at high spin values in the odd-Z nuclei are of special interest, because of the large intrinsic proton g-factors.

In this article detailed information concerning the level scheme of the odd-Z nucleus ^{165}Lu is presented. Prior to the present investigation nothing was known about the level structure of this nucleus. A preliminary report of these data was presented in ref.¹⁰).

2. Experiments

High-spin states in ^{165}Lu have been studied at the Niels Bohr Institute FN tandem accelerator using the reaction $^{153}\text{Eu}(^{16}\text{O}, 4n)$.

By looking at the radioactive decay, the bombarding energy being 82 MeV, it could be concluded that the ratio between the two main reaction channels emitting 4 and 3 neutrons

is approximately 4 to 1. In the coincidence experiment some transitions belonging to Yb nuclei were recognized and it could be concluded that a few percent of the reaction are going through the pxn exit channels. Therefore this reaction is very favourable for producing the nucleus ^{165}Lu .

Gamma-gamma coincidences were measured at a bombarding energy of 84 MeV using five Ge(Li) detectors in anti-Compton shields and one NaI(Tl) crystal as a multiplicity filter. The target used was isotopically enriched (98.76%) metallic ^{153}Eu with a thickness of 5 mg/cm^2 . The experimental set-up¹¹⁾ and the analysis procedure⁷⁾ have been described elsewhere. Coincidence spectra showing the different cascades in ^{165}Lu are presented in fig. 1.

Excitation functions were measured in the bombarding energy range 73-85 MeV using the same target as in the coincidence experiment. Singles γ -ray spectra were recorded by a Ge(Li) detector. The intensity of γ -rays assigned to ^{165}Lu is increasing with increasing bombarding energy in this range.

The angular distribution of the γ -rays was measured by two different detectors. A Ge(Li) detector in a Compton-suppressed mode surrounded by a BGO shield and a single low-energy small volume photon detector (LEP) were used. The detectors were set at five different angles between 0° and 90° . A Ge(Li) detector placed in the backward direction served as a monitor. The efficiency calibrations

at the different angles were performed with radioactive ^{152}Eu and ^{133}Ba sources placed at the target position. The normalized intensities were fitted with the expression $\omega(\theta) = A_0 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta)$. The good resolution of the LEP detector made it possible to resolve many close lying γ -rays at low energies, that is below about 300 keV. Thus, angular distribution coefficients and relative intensities could be calculated for a number of low energy γ -rays, for which the Compton-suppressed Ge(Li) detector did not give any results. For transitions that were observed in both detectors the coefficients were in agreement. The results of the angular distribution measurements are given in table 1. The assignment of the transitions is discussed in subsect. 3.1.

In order to look for possible low-energy delayed transitions, connecting the different bands, a gamma-time experiment was done. A low-energy photon detector and a pulsed beam with 500 ns or 2 μs between the pulses were used. Two delayed transitions with energies of 83 keV and 89 keV and with half-lives around 100 ns and 500 ns, respectively, were seen. The 83 keV transition is connected, through coincidence relations, to an unassigned band (maybe in ^{166}Lu) whereas the position of the 89 keV transition is not yet known. Spectra recorded after the beam had been switched off were also investigated in order to look for possible transitions from long-lived states. No such transitions were observed except the ones already known from the radioactive decay of ^{165}Lu and ^{166}Lu . Consequently, no delayed transitions have been assigned to

^{165}Lu so far, although some should be expected.

3. Construction of the level scheme

3.1. Assignments

The assignment of γ -ray cascades to ^{165}Lu is based on the observation that most of the intensity belongs to either ^{165}Lu or ^{166}Lu . It is then required that the excitation functions should not be compatible with an assignment to ^{166}Lu . As can be seen in fig. 2 five rotational bands have thus been identified as belonging to ^{165}Lu . In four of these bands both signatures are seen. The assignment of these bands to different Nilsson orbits is based on the systematics of level energies for the heavier even-N Lu isotopes $^{12-17}\text{Lu}$). The ordering of the transitions is determined from intensity relations and by using coincidence relations for transitions connecting different bands. Spins and parities have been assigned to all levels assuming cascades of stretched E2 transitions. In the lower parts of the bands this assumption is supported for quite many transitions by the results of the angular distribution measurement (see table 1). In the higher parts of the bands this assumption is less well founded and the spin and parity assignments (fig. 2) are put in brackets, when either no angular distributions could be obtained or the lines involved are very complex. These assumptions on which spin and parity assignments are based should be kept in mind when reading the following

sections.

3.2. The ground state of ^{165}Lu

The isotope ^{165}Lu has earlier been identified in radioactive decay studies and its half-life determined to $11.8 \pm 0.5 \text{ min}^{18}$). With the atomic beam magnetic resonance method Ekström et al 19) obtained resonance signals decaying with this half-life at frequencies corresponding to a nuclear spin $I=1/2$. This has also been confirmed by Adam et al 20). In the heavier even-N Lu nuclei the ground state levels are assigned as $7/2^+$. In the even-N Lu isotopes, $^{167-175}\text{Lu}$, the energy of the $1/2^+(411)$ level is decreasing, relative to the ground-state level $7/2^+(404)$, with decreasing neutron number. In ^{167}Lu it is so close to the $7/2^+(404)$ level that the connecting transition has not been observed and in ^{165}Lu Nilsson model calculations 21) predict a $1/2^+(411)$ level quite close to the $7/2^+(404)$ state. From the present study it can be concluded that if the ground state has spin $1/2$ it must be the $1/2^+$ member of the $1/2^+(411)$ band. By looking at ^{167}Lu this state is expected to lie about 20 keV lower than the $3/2^+$ level of that band. No transitions, however, have been seen feeding that level. Most of the intensity of the $5/2^+(411)$ level in ^{165}Lu is feeding the $3/2^+$ level. Other levels possibly feeding the ground state should be expected to lie very close to it in energy.

3.3. The bands built on the $1/2^+(411)$, $5/2^+(402)$ and $1/2^-(541)$ Nilsson states

The rotational structure built on the $1/2^+(411)$ Nilsson orbital is established from the $3/2^+$ to the $27/2^+$ level. Both signatures, $\alpha=1/2$ and $\alpha=-1/2$ are seen and the corresponding bands are classified as $(+,+)_1$ and $(+,-)_1$, respectively*.

There are two probable E2 transitions feeding the $23/2^+$ level with almost the same energy, and similar intensities. It cannot be concluded definitely from this study which one of them that belongs to this band. The other transition is probably depopulating the $27/2^+$ level of the $5/2^+(402)$ band.

* The rotational configurations $(\pi\alpha)_n^S$ are labelled by the conserved quantum numbers of the corresponding intrinsic quasiparticle configurations, parity, π , and signature, α (+ or - corresponds to $\alpha=1/2$ or $\alpha=-1/2$; when $\alpha=1$ or 0 it is explicitly stated). The subscript n designates that this configuration is the n th such configuration with these quantum numbers. A superscript S is added to multi-quasiparticle states to designate the seniority of the configuration. It should be noted that the subscript n is not certain for this nucleus because the cascades are not all connected. However, the most likely n is assigned to each band.

The $(+,+)_2$ and $(+,-)_2$ bands built on the $5/2^+(402)$ state are observed up to the $21/2^+$ and $(23/2^+)$ levels, respectively. Three transitions have been tentatively placed as shown in the level scheme (fig. 2). The 555 keV and 460 keV transitions, which are in coincidence with each other, are placed on top of the $21/2^+$ level and the 476 keV transition is suggested to connect the 2296 keV level with the 1819 keV level of the $(+,+)_1$ band. Furthermore, the location of the $27/2^+$ level has been tentatively suggested as mentioned earlier. The ordering of the transitions is well established from the coincidence results but the angular distribution coefficients can only be obtained for very few transitions within this band, partly due to its weak population in this reaction and partly due to contaminations from radioactive decay and other lines.

For the $1/2^-(541)$ Nilsson state only the $(-,+)_2$ band with the signature $\alpha=1/2$ is seen. Systematics and angular distribution data give spin and parity for the members of this cascade up to $25/2^-$. The tentative assignment of higher lying levels, up to $41/2^-$, is made assuming that they belong to this band. The ordering of the four highest transitions is determined from the coincidence relations.

The bands discussed so far are clearly interconnected and the relative positions of their levels well established.

3.4. The bands built on the $7/2^+(404)$ and $9/2^-(514)$ Nilsson states

The bands $(+,+)_3$ and $(+,-)_3$ built on the $7/2^+(404)$ Nilsson orbital are followed up to the $(33/2^+)$ and $(31/2^+)$ levels. One weak transition of 480 keV is seen feeding into one of these bands close to the backbending region. Its definite position cannot be given.

The $(-,+)_1$ and $(-,-)_1$ bands built on the $9/2^-(514)$ Nilsson state are observed up to the $(41/2^-)$ and $43/2^-$ members. The upper parts of these bands contain many transitions that are multiply placed or contain contaminations. Nevertheless the ordering is firmly established from the results of the coincidence experiments and the energy sums.

The sum of the relative intensities feeding and depopulating the $11/2^-$ and $9/2^-$ levels is far from being in balance. It can therefore be concluded that some low energy transitions, not seen, are depopulating and populating the $11/2^-$ and $9/2^-$ levels, respectively.

A strong transition of 180 keV is depopulating the $9/2^-$ level. At this stage it can only be tentatively suggested that this transition is feeding the $7/2^-(523)$ state which is expected at a rather low energy in this nucleus.

These positive and negative parity bands are interconnected via two transitions one strong and one

weak, so the relative energies of the levels in these bands can be established.

Their position relative the other group of bands is unfortunately not known. But since connecting transitions have not been observed they are expected to have low energies ($\lesssim 40$ keV).

4. Discussion

In order to study the effect of the rotation on the independent-particle motion in deformed nuclei, the level energies observed in the laboratory system can be transformed to excitation energies, e' , in the rotating intrinsic frame. The routhians thus display these energies as a function of the angular frequency $\hbar\omega$. This makes a comparison between different nuclei and a comparison with the cranked shell model (CSM) ^{22,23} possible. The detailed prescription for this transformation is given in ref. ²³). In odd-N or odd-Z nuclei the routhians are referred to the reference configuration of the neighbouring even-even nucleus and the pairing correlation parameter Δ is added ²³). If a ground-state reference is used a parametrized ground-state band described by the Harris ²⁴) formula

$$\mathcal{J} = \mathcal{J}_0 + \omega^2 \mathcal{J}_1$$

is chosen. The moment of inertia parameters are given the values $\mathcal{J}_0 = 25.8 \text{ MeV}^{-1} \hbar^2$ and $\mathcal{J}_1 = 90 \text{ MeV}^{-3} \hbar^4$ for ^{165}Lu . The routhians for the different bands in ^{165}Lu are presented

in fig. 3. The alignments ($i_x = -de'/d\omega$) as a function of the angular frequency $\hbar\omega$ are plotted in fig. 4. At this stage only the variations in the crossing frequencies are discussed.

The crossing frequency for the $(+,+)_3$ and $(+,-)_3$ bands is at about 0.275 MeV as expected. It is the first pair of $i_{13/2}$ neutrons that is responsible for this crossing. It should occur at the same frequency as the g-band S-band crossing in the even-even nuclei, since the quasiproton should not change the neutron pairing correlation parameter. On the other hand, in odd-N nuclei, this crossing frequency is reduced by about 40 keV which has been explained as a reduction in pairing²⁵⁾, due to the quasineutron.

The $(-,+)_2$ band is observed up to the backbending region and a lower limit of about 0.32 MeV can be set for the crossing frequency (fig. 3.). This delay in the crossing frequency in this band built on the $1/2^-(541)$ Nilsson state has been observed earlier for several nuclei. This behaviour can be partially explained by increased deformation. It has been calculated²⁶⁾ that an increase in ϵ , in the $1/2^-(541)$ configuration, by about 0.035 causes an increase in the crossing frequency by about 0.035 MeV but this alone does not explain the whole increase in the crossing frequency. Furthermore, no calculation on the change in deformation with frequency has been done for this band so far.

The crossing frequency in the $(-,+)_1$ and $(-,-)_1$ bands is reduced by about 20 keV, compared with the crossing frequency in the $(+,+)_3$ and $(+,-)_3$ bands. This is surprising since the same pair of $i_{13/2}$ neutrons is involved. It is therefore clear from these observations, that there is a considerable variation in the crossing frequency, due to the first pair of $i_{13/2}$ neutrons, depending on what proton configuration is involved. This cannot be satisfactorily explained at the moment.

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Table 1

The γ -ray energies, intensities and angular distribution coefficients for the transitions assigned to ^{165}Lu following the $^{153}\text{Eu}(^{16}\text{O}, 4n)$ reaction at 84 MeV.

E_γ a) (keV)	I_γ^{rel} b)	Ang. dist. coeff. c)		Assignments d)	
		A_2/A_0	A_4/A_0	I_i^π, K_i^π	$\rightarrow I_f^\pi, K_f^\pi$
100.4	279	0.04 (03)	-0.04 (03)	$11/2^-, 9/2^-$	$9/2^-, 9/2^-$
121.1	53 e)			$9/2^-, 1/2^-$	$5/2^-, 1/2^-$
136.2	213	-0.04 (03)	0.04 (03)	$7/2^+, 5/2^+$	$5/2^+, 5/2^+$
147.4	120	-0.26 (05)	0.03 (05)	$5/2^+, 1/2^+$	$3/2^+, 1/2^+$
152.6	60	-0.21 (07)	-0.05 (07)	$11/2^-, 9/2^-$	$9/2^+, 7/2^+$
159.1	556 e)	0.18 (02)	-0.01 (02)	$9/2^+, 7/2^+$	$7/2^+, 7/2^+$
159.3	770 e)			$13/2^-, 9/2^-$	$11/2^-, 9/2^-$
164.2	160	-0.06 (04)	-0.01 (04)	$9/2^+, 5/2^+$	$7/2^+, 5/2^+$
167.9	648	-0.01 (02)	-0.01 (02)	$15/2^-, 9/2^-$	$13/2^-, 9/2^-$
175.0	55	-0.32 (11)	0.06 (12)	$13/2^-, 1/2^-$	$11/2^+, 1/2^+$
180.1	1000	0.16 (02)	-0.02 (02)	$9/2^-, 9/2^-$	
184.2	367	0.32 (03)	-0.01 (03)	$11/2^+, 7/2^+$	$9/2^+, 7/2^+$
193.3	86 e)			$11/2^+, 5/2^+$	$9/2^+, 5/2^+$
195.3	529	0.29 (02)	-0.07 (02)	$7/2^+, 1/2^+$	$3/2^+, 1/2^+$
206.3	527	0.01 (02)	-0.01 (02)	$19/2^-, 9/2^-$	$17/2^-, 9/2^-$
207.8	153	0.38 (06)	-0.01 (05)	$13/2^+, 7/2^+$	$11/2^+, 7/2^+$
210.0	222	-0.13 (03)	0.00 (03)	$35/2^-, 9/2^-$	$33/2^-, 9/2^-$
211.3	995	-0.27 (02)	0.00 (02)	$9/2^-, 9/2^-$	$7/2^+, 7/2^+$
212.8	60	0.12 (15)	0.04 (15)	$13/2^+, 5/2^+$	$11/2^+, 5/2^+$
227.1 f)				$(37/2^-, 9/2^-)$	$35/2^-, 9/2^-$
228.1	132 e)	0.18 (02)	-0.07 (02)	$15/2^+, 7/2^+$	$13/2^+, 7/2^+$
228.2	576 e)			$13/2^-, 1/2^-$	$9/2^-, 1/2^-$
230.8	556	0.10 (02)	-0.01 (02)	$17/2^-, 9/2^-$	$15/2^-, 9/2^-$
231.9	263	-0.04 (03)	0.02 (03)	$23/2^-, 9/2^-$	$21/2^-, 9/2^-$
237.0	90	-0.41 (11)	0.00 (12)	$9/2^+, 1/2^+$	$7/2^+, 1/2^+$
241.9 f)				$17/2^+, 5/2^+$	$15/2^+, 5/2^+$
244.5 f)				$15/2^+, 5/2^+$	$13/2^+, 5/2^+$
247.1	89	0.29 (11)	-0.08 (11)	$17/2^+, 7/2^+$	$15/2^+, 7/2^+$
249.6	159	-0.14 (07)	-0.01 (07)	$33/2^-, 9/2^-$	$31/2^-, 9/2^-$

Table 1 (continued)

E _γ a) (keV)	I _γ ^{rel} b)	Ang. dist. coeff. c)		Assignments d)	
		A ₂ /A ₀	A ₄ /A ₀	I _i ^π , K _i ^π	I _f ^π , K _f ^π
251.2	118	-0.11 (09)	0.05 (10)	27/2 ⁻ , 9/2 ⁻	25/2 ⁻ , 9/2 ⁻
254.2	116	-0.25 (09)	0.07 (09)	31/2 ⁻ , 9/2 ⁻	29/2 ⁻ , 9/2 ⁻
259.7	309	0.20 (05)	-0.09 (05)	13/2 ⁻ , 9/2 ⁻	9/2 ⁻ , 9/2 ⁻
259.8				39/2 ⁻ , 9/2 ⁻	(37/2 ⁻ , 9/2 ⁻)
261.1 f)				21/2 ⁺ , 5/2 ⁺	(19/2 ⁺ , 5/2 ⁺)
261.8	95 e)			19/2 ⁺ , 7/2 ⁺	17/2 ⁺ , 7/2 ⁺
271.1	556 e) weak }	-0.19 (03)	0.00 (03)	9/2 ⁻ , 1/2 ⁻	7/2 ⁺ , 1/2 ⁺
271.5				29/2 ⁺ , 7/2 ⁺	27/2 ⁺ , 7/2 ⁺
275.2	140	-0.12 (08)	0.01 (08)	(41/2 ⁻ , 9/2 ⁻)	39/2 ⁻ , 9/2 ⁻
276.7	116	0.15 (09)	-0.07 (09)	21/2 ⁺ , 7/2 ⁺	19/2 ⁺ , 7/2 ⁺
281.4 f)				(19/2 ⁺ , 5/2 ⁺)	17/2 ⁺ , 5/2 ⁺
284.9	66 e)	0.17 (07)	0.01 (08)	23/2 ⁺ , 7/2 ⁺	21/2 ⁺ , 7/2 ⁺
284.9	123 e)			9/2 ⁺ , 1/2 ⁺	5/2 ⁺ , 1/2 ⁺
287.2	436	0.07 (04)	-0.02 (04)	21/2 ⁻ , 9/2 ⁻	19/2 ⁻ , 9/2 ⁻
292.4	56	0.34 (10)	-0.12 (10)	27/2 ⁺ , 7/2 ⁺	25/2 ⁺ , 7/2 ⁺
295.0	65	0.34 (09)	-0.04 (08)	25/2 ⁺ , 7/2 ⁺	23/2 ⁺ , 7/2 ⁺
300.4	64	0.38 (09)	-0.14 (08)	9/2 ⁺ , 5/2 ⁺	5/2 ⁺ , 5/2 ⁺
301.8	41	-0.08 (14)	-0.12 (16)	13/2 ⁺ , 1/2 ⁺	11/2 ⁺ , 1/2 ⁺
312.3	81	0.06 (09)	0.07 (09)	43/2 ⁻ , 9/2 ⁻	(41/2 ⁻ , 9/2 ⁻)
324.3	332	0.27 (06)	-0.10 (06)	11/2 ⁺ , 1/2 ⁺	7/2 ⁺ , 1/2 ⁺
326.8	288 e)	0.20 (03)	-0.03 (03)	25/2 ⁻ , 9/2 ⁻	23/2 ⁻ , 9/2 ⁻
327.2	370 e)			15/2 ⁻ , 9/2 ⁻	11/2 ⁻ , 9/2 ⁻
335.4	447	0.24 (03)	-0.08 (03)	17/2 ⁻ , 1/2 ⁻	13/2 ⁻ , 1/2 ⁻
339.2	196	0.01 (04)	0.03 (04)	29/2 ⁻ , 9/2 ⁻	27/2 ⁻ , 9/2 ⁻
343.3	340	0.26 (04)	-0.07 (04)	11/2 ⁺ , 7/2 ⁺	7/2 ⁺ , 7/2 ⁺
345.3	weak			5/2 ⁻ , 1/2 ⁻	3/2 ⁺ , 1/2 ⁺
349.3	53	-0.01 (11)	0.10 (12)	17/2 ⁺ , 1/2 ⁺	15/2 ⁺ , 1/2 ⁺
357.5	49 e)			11/2 ⁺ , 5/2 ⁺	7/2 ⁺ , 5/2 ⁺
389.1	123	0.27 (08)	-0.10 (08)	13/2 ⁺ , 1/2 ⁺	9/2 ⁺ , 1/2 ⁺
392.0	503	0.25 (03)	-0.09 (03)	13/2 ⁺ , 7/2 ⁺	9/2 ⁺ , 7/2 ⁺
398.7	508	0.31 (03)	-0.11 (03)	17/2 ⁻ , 9/2 ⁻	13/2 ⁻ , 9/2 ⁻
406.1	104	0.30 (05)	-0.13 (05)	13/2 ⁺ , 5/2 ⁺	9/2 ⁺ , 5/2 ⁺
424.0	239	0.28 (03)	-0.15 (03)	15/2 ⁺ , 1/2 ⁺	11/2 ⁺ , 1/2 ⁺
432.6	297	0.29 (07)	-0.08 (07)	21/2 ⁻ , 1/2 ⁻	17/2 ⁻ , 1/2 ⁻
435.9	356 e)	0.19 (02)	-0.03 (02)	15/2 ⁺ , 7/2 ⁺	11/2 ⁺ , 7/2 ⁺
436.9	72 e)			15/2 ⁺ , 5/2 ⁺	11/2 ⁺ , 1/2 ⁺
437.1	741 e)			19/2 ⁻ , 9/2 ⁻	15/2 ⁻ , 9/2 ⁻
437.1	165 e)			(37/2 ⁻ , 9/2 ⁻)	33/2 ⁻ , 9/2 ⁻

Table 1 (continued)

E_Y a) (keV)	I_Y^{rel} b)	Ang. dist. coeff. c)		Assignments d)	
		A_2/A_0	A_4/A_0	I_1^π, K_1^π	I_f^π, K_f^π
444.4	107	0.41 (06)	-0.15 (06)	$15/2^+, 1/2^+$	$11/2^+, 5/2^+$
457.3	59	0.54 (15)	0.15 (14)	$15/2^+, 5/2^+$	$11/2^+, 5/2^+$
459.6	206 e)	0.26 (04)	-0.05 (04)	$35/2^-, 9/2^-$	$31/2^-, 9/2^-$
460	weak }			$(29/2^+, 5/2^+)$	$25/2^+, 5/2^+)$
471.5	163	0.33 (11)	0.01 (11)	$17/2^+, 1/2^+$	$13/2^+, 1/2^+$
475.2	493	0.28 (02)	-0.08 (02)	$17/2^+, 7/2^+$	$13/2^+, 7/2^+$
476	weak			$(25/2^+, 5/2^+)$	$21/2^+, 1/2^+)$
480	weak			Feeding the $(+, \pm)_3$ band	
486.4	165 e)	0.22 (03)	-0.07 (03)	$17/2^+, 5/2^+$	$13/2^+, 5/2^+$
486.9	144 e)			$39/2^-, 9/2^-$	$35/2^-, 9/2^-$
493.5	563	0.24 (02)	-0.08 (02)	$21/2^-, 9/2^-$	$17/2^-, 9/2^-$
502.3	356	0.24 (04)	-0.08 (04)	$19/2^+, 1/2^+$	$15/2^+, 1/2^+$
503.8	186	0.23 (06)	-0.05 (06)	$33/2^-, 9/2^-$	$29/2^-, 9/2^-$
508.9	370 e)			$19/2^+, 7/2^+$	$15/2^+, 7/2^+$
516.5	235	0.18 (06)	-0.13 (06)	$25/2^-, 1/2^-$	$21/2^-, 1/2^-$
519.1	802	0.21 (02)	-0.09 (02)	$23/2^-, 9/2^-$	$19/2^-, 9/2^-$
523.3 f)				$(19/2^+, 5/2^+)$	$15/2^+, 5/2^+$
526.5	141	0.24 (08)	-0.10 (08)	$21/2^+, 1/2^+$	$17/2^+, 1/2^+$
530.8	76	0.19 (13)	-0.14 (13)	$25/2^+, 1/2^+$	$21/2^+, 1/2^+$
535.0 f)				$(41/2^-, 9/2^-)$	$(37/2^-, 9/2^-)$
538.5	479	0.30 (03)	-0.09 (03)	$21/2^+, 7/2^+$	$17/2^+, 7/2^+$
542.5	155 g)	0.28 (06)	-0.12 (06)	$21/2^+, 5/2^+$	$17/2^+, 5/2^+$
545.0	343	0.27 (03)	-0.10 (03)	$23/2^+, 1/2^+$	$19/2^+, 1/2^+$
548.4	165	0.22 (07)	-0.11 (07)	$27/2^+ (1/2^+)$	$23/2^+, 1/2^+$
555	weak	0.18 (07)	-0.08 (08)	$(25/2^+, 5/2^+)$	$21/2^+, 5/2^+)$
555.1	102 e)			$27/2^+, (5/2^+)$	$23/2^+, 1/2^+$
558.7	387	0.27 (04)	-0.09 (04)	$25/2^-, 9/2^-$	$21/2^-, 9/2^-$
561.6	427	0.31 (03)	-0.12 (03)	$23/2^+, 7/2^+$	$19/2^+, 7/2^+$
563.9	369	0.41 (04)	-0.12 (04)	$29/2^+, 7/2^+$	$25/2^+, 7/2^+$
569.0 f)				$(31/2^+, 7/2^+)$	$27/2^+, 7/2^+$
570.2 f)				$(23/2^+, 5/2^+)$	$(19/2^+, 5/2^+)$
578.0	643	0.24 (03)	-0.11 (03)	$27/2^-, 9/2^-$	$23/2^-, 9/2^-$
579.9	369	0.28 (04)	-0.10 (04)	$25/2^+, 7/2^+$	$21/2^+, 7/2^+$
585.2	140 e)	0.24 (05)	-0.07 (05)	$(29/2^-, 1/2^-)$	$25/2^-, 1/2^-$
587.4	247 e)			$27/2^+, 7/2^+$	$23/2^+, 7/2^+$
587.5	119 e)			$43/2^-, 9/2^-$	$39/2^-, 9/2^-$

Table 1 (continued)

E_Y a) (keV)	I_Y^{rel} b)	Ang. dist. coeff. c)		Assignments d)	
		A_2/A_0	A_4/A_0	I_i^{π}, K_i^{π}	I_f^{π}, K_f^{π}
590.4	309	0.34(05)	-0.13(05)	$29/2^-$, $9/2^-$	$25/2^-$, $9/2^-$
593.4	314	0.24(06)	-0.12(06)	$31/2^-$, $9/2^-$	$27/2^-$, $9/2^-$
598.6 f)				$(33/2^+$, $7/2^+)$	$29/2^+$, $7/2^+$
629.1	41 e)			$(41/2^-$, $1/2^-)$	$(37/2^-$, $1/2^-)$
631.5	74 e)			$(33/2^-$, $1/2^-)$	$(29/2^-$, $1/2^-)$
659.0	62 e)			$(37/2^-$, $1/2^-)$	$(33/2^-$, $1/2^-)$

- a) The energies are accurate to within 0.2 keV for strong well resolved lines ($I_Y^{\text{rel}} \gtrsim 150$). For other lines the uncertainty may rise to 0.6 keV.
- b) Normalized to 1000 for the 180.1 keV line. Estimated uncertainties are less than 10% for strong well resolved lines ($I_Y^{\text{rel}} \gtrsim 150$). For other lines they may rise to 30%.
- c) Uncertainties from the fitting procedure are given in brackets. The total uncertainties are usually considerably larger.
- d) The assignment of the different bands to Nilsson orbitals is based on the systematics of level energies of even-N Lu nuclei. Spin and parity has been assigned to all levels assuming cascades of stretched E2 transitions. See discussion in subsection 3.1.
- e) From coincidence data, not corrected for possible angular correlation effects.
- f) No intensities can be obtained for these transitions because of complex spectra or contaminations.
- g) Includes small contamination.

Figure captions

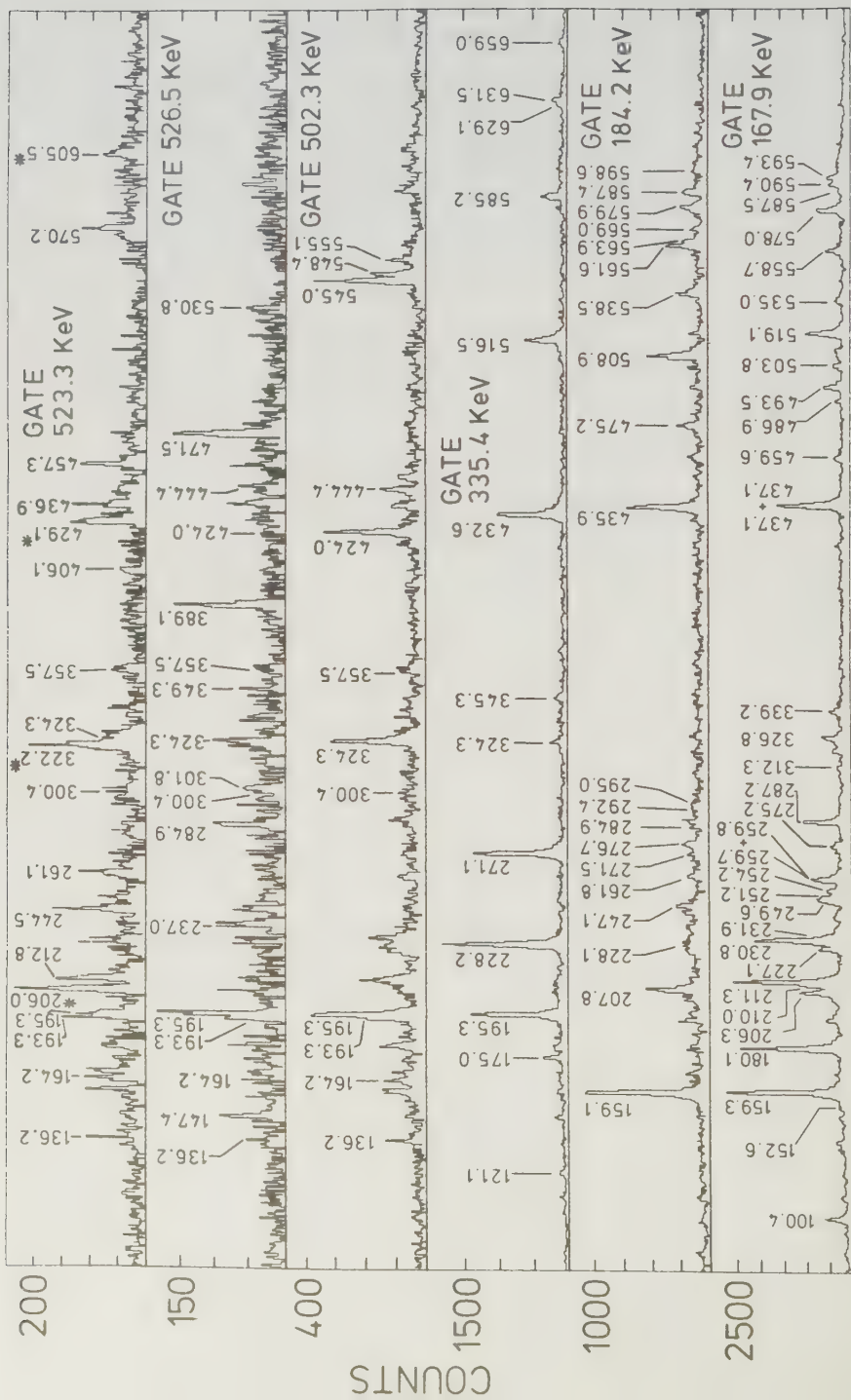
Fig. 1. Examples of γ - γ coincidence spectra from the $^{153}\text{Eu}(^{16}\text{O},4n)$ reaction at a bombarding energy of 84 MeV. The energies marked in the spectra are those whose coincidence relations with the gated γ -ray have been established. In a few cases these peaks are either very weak or hardly seen at all indicating a very weak coincidence relation. In these cases the coincidences between the gated γ -ray and the marked γ -ray are established by gating on other transitions. When gating with a γ -radiation at 502 keV most of the peaks not marked are due to the 504 keV transition in the $(-, \pm)_1$ bands. The peaks marked with a star in the 523 keV gate are due to transitions in ^{165}Yb produced via the $p3n$ reaction channel.

Fig. 2. The level scheme of ^{165}Lu showing states populated in the $^{153}\text{Eu}(^{16}\text{O},4n)$ reaction at 84 MeV. The assignment of the bands to Nilsson orbitals is based on the systematics of level energies of even-N Lu nuclei. Spin and parity has been assigned to all levels assuming cascades of stretched E2 transitions. See subsect. 3.1.

Fig. 3. Experimental routhians for the different bands in ^{165}Lu . The Harris parameters used are

$$\mathcal{J}_0 = 25.8 \text{ MeV}^{-1} \hbar^2 \text{ and } \mathcal{J}_1 = 90 \text{ MeV}^{-3} \hbar^4$$

Fig. 4. Experimental alignments for the different bands in ^{165}Lu . For Harris parameters, see fig. caption 3.



E_γ

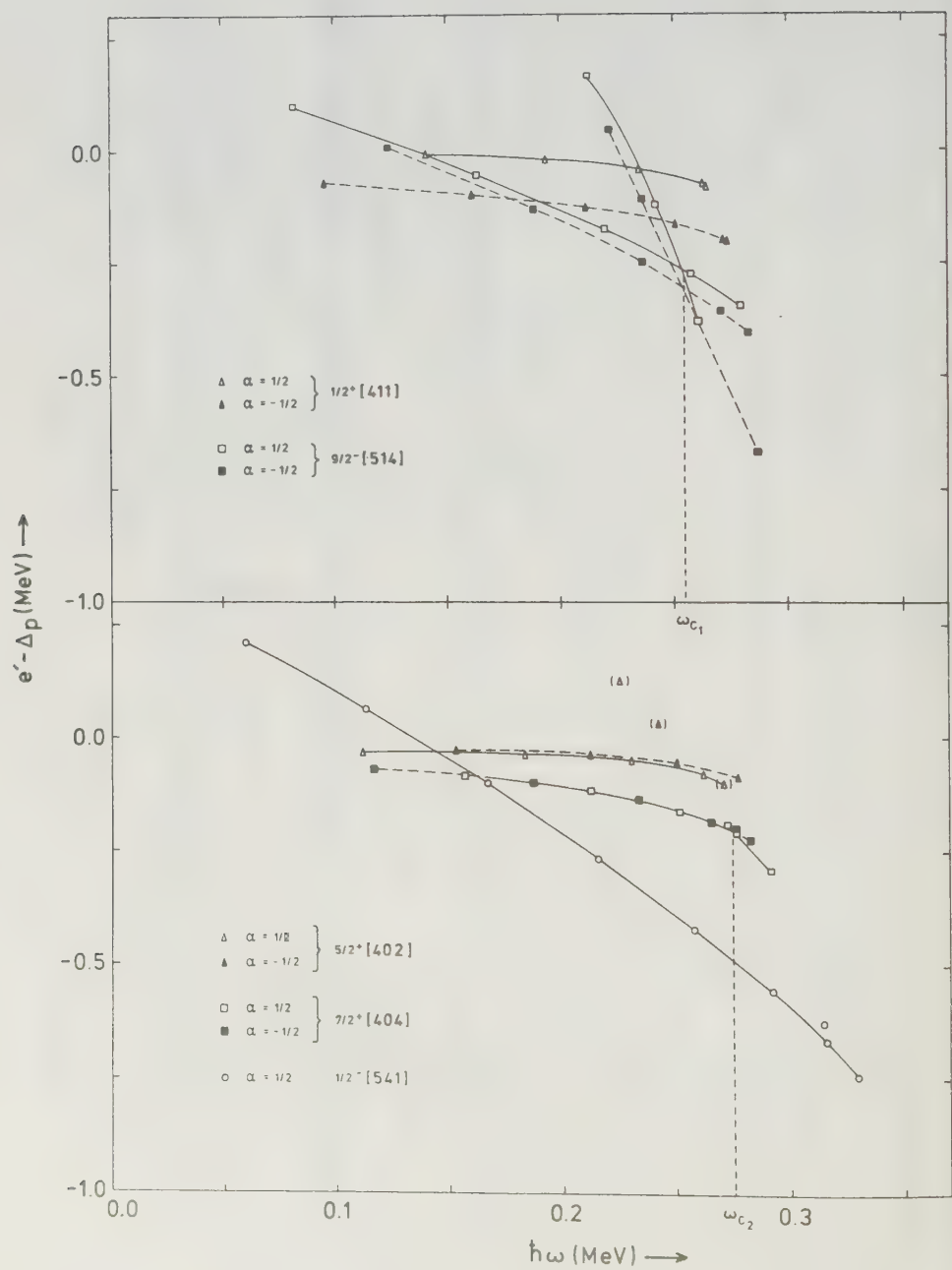


FIG. 3

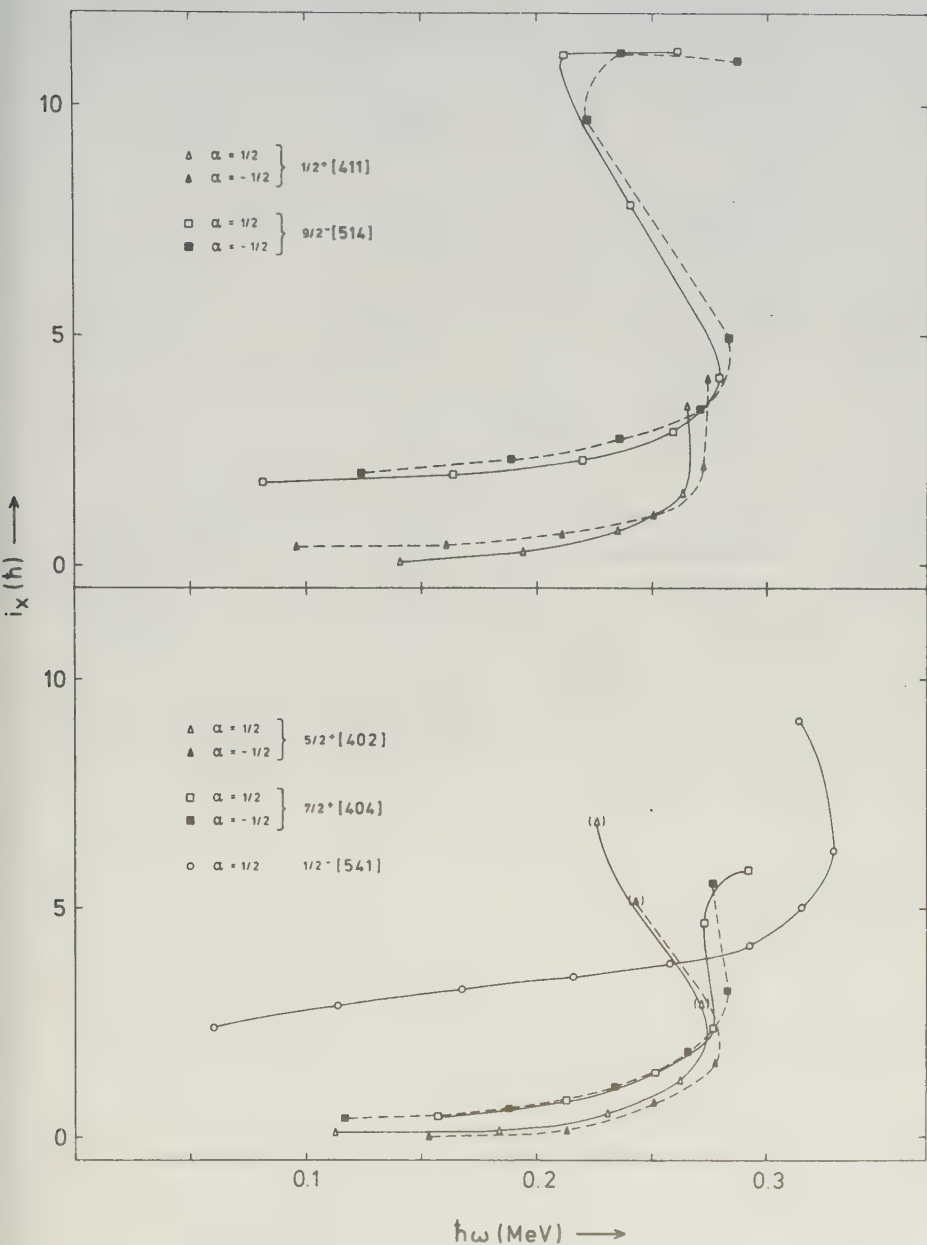


FIG. 4

Dokumentutgivare
UNIVERSITY OF LUND
Handläggare Department of Physics

Dokumentnamn
Internal report
Utgivningsdatum

Dokumentbeteckning
LUNFD6/(NFFK-7028)
Ärendebeteckning

Författare S. Jönsson,
J. Lyttkens,
L. Carlén,
N. Roy,
H. Ryde,
W. Waluś,
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G.B. Hagemann,
B. Herskind,
J.D. Garrett and P.O. Tjøm.

Dokumenttitel och undertitel

Experimental results on the study of High-Spin States in ^{165}Lu .

Referat (sammandrag)

High-spin states in ^{165}Lu have been populated in the $^{153}\text{Eu}(^{16}\text{O}, \text{n})$ reaction. An excitation function measurement was made to assign correct γ -rays to ^{165}Lu . A level scheme was constructed from the studies of γ - γ coincidences, and the measurement of γ -ray angular distributions. Five rotational bands have been assigned to ^{165}Lu , and identified as the ones built on the $5/2^+(402)$, $1/2^+(411)$, $1/2^-(541)$, $7/2^+(404)$ and $9/2^-(514)$ Nilsson states. Both signatures are seen for all of them except the one built on the $1/2^-(541)$ Nilsson orbital. The crossing frequencies, for the bands observed above backbending, are determined and the variation in the crossing frequency is discussed.

Referat skrivat av
The authors.

Förslag till ytterligare nyckelord

Klassifikationssystem och -klass(er)

Indextermer (ange källa)

Omfång 21 pages;
4 figures. Övriga bibliografiska uppgifter
Språk English

Sekretessuppgifter

ISSN

0348-9329

ISBN

Dokumentet kan erhållas från
Department of Cosmic and Subatomic Physics
University of Lund,
Sölvegatan 14; S-223 62 LUND, Sweden.

Mottagarens uppgifter

Price

Blankett LU 11:25 1976-07

Errata

	Page	Replace	By
Paper I	167 , fig. 8	25/2	25/2 ⁻
Paper II	330 , + 1	(h _{11/2})	(h _{9/2})
	330 , ref. 2	23.000	24,158
	330 , ref. 14	23,000	24,164
	330 , ref. 14	Milsson	Nilsson
Paper III	140 , fig. 7a	39/2 ⁻	31/2 ⁻
	155 ,	wrthin	within
Paper IV	283 , fig. 10	1/2	1/2 ⁻

